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Evolved Navigation Theory and the Environmental Vertical Illusion.

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Evolved Navigation Theory and the Environmental Vertical Illusion

by

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Dedication

I dedicate my graduate work to my mother, to my wife, and to my best friend, in no particular order. Hopefully there is no confusion as to who holds each of those titles.

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Evolved Navigation Theory and the Environmental Vertical Illusion.

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These studies suggested that everyday visual perception is unconsciously subject to large-scale illusions on ubiquitous environmental surfaces. Participants overestimated environmentally vertical surfaces and did so to an increasing degree with longer surfaces, neither of which occurred with environmentally horizontal surfaces. I title this illusion the *environmental vertical illusion*. The severity of previous injury from a fall related to the degree of illusion such that more severe previous falling injuries were associated with lower illusion magnitudes, even though the illusion is still present at higher injury severities. I predicted these data from hypotheses derived from Evolved Navigation Theory (ENT), which focuses on how navigational costs over evolutionary time can shape cognitive and perceptual mechanisms.

Virtual reality data suggested that unrealistically artificial falling costs failed to produce the environmental vertical illusion, even on apparently vertical surfaces. Virtual reality methods also suggested that distance estimation from immobile visual displays

deviated from natural distance estimation in important ways that hold implications for tasks involved in piloting and surgery. Data from physical and virtual reality suggested that no clear relationship existed between the 2D Vertical-Horizontal Illusion and 3D distance estimates gathered here.

The current findings hold implications outlined under ENT for areas such as anxiety disorders, piloting, surgery, individual differences, and visual stimuli design. However, these findings may be most important because distance and orientation perception occurs constantly in most visual systems and, consequently, most behaviors. Understanding how distance perception occurs thus helps us to understand one of the most common of all psychological experiences. These data suggest that a primary component of human visual experience is illusory. However, through the use of a theory rooted in evolution (ENT), we may be able to predict and better understand these important features of human psychology.

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Introduction

Evolutionary scientists often investigate how the costs of exhibiting an adaptation may indicate why the adaptation arose and how it functions. Behavioral scientists study a variety of adaptations involved in a variety of behaviors such as parenting, communication, or mating. The costs of parenting, communication, mating, and other behaviors, however, are preceded by the costs of navigation. Animals must navigate their environments in order to perform most behaviors, making navigational costs powerful factors in shaping broad areas of cognition.

The understanding that navigational costs are obligatory in performing most animal behaviors begs the question of what those costs are. An important navigational cost is that of energy. Energy spent on navigation is unavailable for performing other behaviors. Energetic demands are major components in how many anthropologists explain different methods of locomotion (Conroy, 1997, p. 227). Energetic demands are ubiquitous costs of navigation; however, they may not be the most significant costs.

Risk of injury during navigation can pose navigation costs that outweigh energetic demands. For example, the energetic demands of walking 30 meters would not likely pose a significant cost for the average adult, but I doubt that anyone would feel comfortable with the costs of falling that same distance. Unlike energy costs, the costs of injury have a very high ceiling that is not easily managed by the organism. Although people can choose to stop walking if they are tired, people cannot choose to stop falling because they are being hurt too much. Risk of injury during navigation can outweigh direct energetic demands.

Many risks of injury directly result from navigational decisions. Navigational choices can take an organism within range of intra- or inter-species aggressors, such as unfriendly neighbors or predators. Navigational choices can also expose an organism to chemical insults such as poisons, or to physical insults such as extreme temperatures or weather, sharp or thorny surfaces, drowning, exposure to falling objects, or the risk of falling.

The question that I investigate here is whether some cognitive mechanisms function to help humans avoid navigational costs associated with a risk of injury.

Perceptual Navigation Cost Theories

Theories that suggest how perceptual mechanisms might account for costs associated with navigation include foreshortening of receding horizontals, 'gravity theory', affordance, and evolved navigation theory.

Foreshortening of Receding Horizontals

Foreshortening of receding horizontals is both a phenomenon and a theory. As a phenomenon, foreshortening of receding horizontals occurs such that (oftentimes horizontal) surfaces extending away from the observer are visually compressed on the retina—they take up less retinal space, compared to their actual size, than surfaces that run perpendicular to the line of sight. Large distances extending away from the observer (i.e. ‘egocentric’ distances) thus appear ‘foreshortened’.

As a theory, however, Segall, Campbell, and Herskovitz (1966) proposed that foreshortening as a phenomenon causes observers to exaggerate distance perceived from egocentric horizontal surfaces in order to increase distance estimation accuracy. The authors contend that overestimation of a foreshortened surface can help to correct the foreshortening. Oftentimes, the majority of surfaces that extend egocentrically away from human observers are horizontal, which extend vertically on the retina. The authors suggest that humans should exaggerate surfaces that appear vertically on the retina in order to estimate accurately. Segall et al. maintain that vertical overestimation should develop among humans in environments with long, receding horizontals, such as those with open vistas, straight roads, and agricultural irrigation.

Contrary to this theory, overestimation of retinally vertical extents reliably develops in all human populations yet studied, including those with minimal receding horizontals, such as the Todas of southern India and Papuans of New Guinea at the turn of the 20th century (Rivers, 1905), as well as jungle-dwelling Peruvians (Bolton, Michelson, Wilde, & Bolton, 1975). Vertical overestimation even occurs in non-humans (chicks, see Winslow, 1933), including non-humans with extensively vertical environments (monkeys, see Dominguez, 1954).

Additionally, Segall et al.’s theory fails to explain the specific overestimation of vertical, as opposed to underestimation of distal horizontal. Predicted from their theory, horizontal lines at the top of a vertical should appear longer than horizontal lines at the bottom of a vertical. Participants, in fact, perceive horizontal line length at the top of a vertical as at least no different from horizontal line length at the bottom (Wober, 1972) and may perceive top horizontals as longer than bottom horizontals (Valentine, 1912).

Furthermore, the vertical overestimation magnitude often observed (roughly 5% overestimation) would fail to compensate sufficiently for the extent of image compression that would be necessary in order to portray accurate horizontal length. Foreshortening cannot serve the purpose hypothesized under this theory. Additionally, we can only able to apply this theory to a subset of navigation costs (energetic expense), because it fails to account for risks of injury associated with navigation.

Gravity Theory

'Gravity theory' (see description by Howard & Templeton, 1966, p. 37) suggests that distance perception translates the energy of locomotion, coupled with the effort to overcome gravity, into perceived distance. This view proposes that greater perceived effort associated with traversing a surface should increase its perceived length, often as a function of the amount of ascending required to traverse the surface.

Gravity theory acknowledges that vertical surfaces require more energy to navigate than horizontal surfaces and suggests that this relationship produces over-perception of vertical surface length in order to portray accurate effort expenditure. Open proponents of gravity theory do not exist, but research of slope steepness estimation appears based in gravity theory.

Slope steepness corresponds with required locomotor energy due to moving against the earth's gravitational force. Gravity theory would predict that upward-sloping surfaces should appear longer than neutral or downward-sloping surfaces. Research suggests that participants visually perceive both upward- *and* downward-sloping surfaces as steeper than the true angle (Proffitt, Bhalla, Gosswiler, & Midgett, 1995). Encumbered and physically disadvantaged participants also over-perceive upward-slope angle more than normal participants (Proffitt, Stefanucci, & Banton, 2003).

Slope steepness research may not extend directly from gravity theory because steepness is not equal to length; gravity theory predicts overestimated length, not steepness, of slopes. Gravity theory also directly predicts distance overestimation at the bottom of a slope, but distance underestimation at the top of the slope because descending requires less effort than climbing and possibly even level walking. However, research suggests greater slope steepness perceived from the top than the bottom of a slope (Proffitt, Bhalla, Gossweiler, & Midgett, 1995). Proffitt et al. depart from gravity theory to explain this one finding with a brief special case explanation that "steep hills are more difficult to descend than ascend," (p 427) and that "A 30 degree hills is about the limit of what we can walk up, and it is too steep to walk down without risk of slipping and falling," (p 409). Slope steepness researchers thus far limit their research to inclines of 30 degrees or less and measure degree of incline instead of length, both of which fail to test gravity theory.

As with foreshortening, gravity theory also applies only to a subset of navigation costs (energetic expense), without accounting for risk of injury.

Affordance

Affordance (Gibson, 1979), broadly suggests that elements in the environment allow (afford) a limited number of behaviors specific to an organism. For example, a ladder might afford behaviors such as climbing to a primate, which the ladder would not afford an elephant. Any aspect of the environment likely affords multiple behaviors—all specified to the individual organism.

Affordance is also suggested to shape perception. An organism may perceive its environment differently in the presence of different affordances. For example, a primate might view a vertical cliff as fairly long if the cliff is difficult to navigate. However, in the presence of a ladder, the primate might perceive less distance from the cliff than without the ladder because the ladder affords lower navigation costs. Related to this, Witt, Proffitt, and Epstein (2004, p. 577) even found that "as the effort associated with walking increases, perceived distance increases if the perceiver intends to walk the extent, but not if the perceiver intends to throw. Conversely, as the effort associated with throwing increases, perceived distance increases if people intend to throw to the target, but not if they intend to walk."

A stipulation of affordance, especially its underlying approach (termed *Ecological Psychology*), is that geometrical illusions are artificial byproducts of impoverished stimuli (Gibson, 1966). Indeed, Gibson suggests that lines on paper are not worthy of the name 'stimulus' at all (Gibson, 1966, p. 313). Gibson suggests that two-dimensional illusions, such as the Muller-Lyer, should disappear when observers view all visual cues that are present when perceiving the object in natural settings. In essence, illusions should decrease as the realism of the stimulus increases.

Gibson suggests the above because he suggests that the richness of sensory information available to organsisms is precisely that which determines how organisms interact with their environments. For example, my perception of what a door is and how to use it could never be fully represented by a mere two-dimensional rectangle—I would never try to ‘open’ the rectangle due to confusing it with a real door. Multiple visual, aural, and haptic cues allow me to open a door; cues unavailable in simple line drawings. The richness of information available in realistic perception vastly exceeds that of line drawings; thus the accuracy with which we interact with the world is contingent upon far more cues than those possible from simple stimuli. Under this approach, illusions present in line drawings represent errors that would not occur in realistic settings. I will return to the support for this assertion in an empirical setting later.

Evolved Navigation Theory

Evolved navigation theory (ENT) (Jackson, 2005; Jackson & Cormack, 2006) is an approach to understanding navigational mechanisms based on the costs of navigation in the environment in which the specific mechanism evolved. Evolved navigation theory suggests that many inherited navigation mechanisms evolved in contexts where variance in gene frequencies corresponded to variance in gene propagation, i.e. those with sufficient or superior environmental navigation abilities ultimately left more offspring than those with inferior abilities. These abilities include any aspect of navigation, including environmental perception, locomotion, navigational decision-making, and others.

Evolved navigation theory is primarily a broad framework for facilitating lower-level predictions; however, ENT itself is directly testable. One method of directly testing ENT is to look at how differences in navigation between sister species may reflect differences in navigational costs. One such natural experiment may exist in land tortoises and sea turtles. Sea turtles primarily navigate aquatic environments and have little chance of mortally flipping onto their backs. Tortoises primarily navigate terrestrial environments and flipping onto their backs poses mortal danger because it is difficult for a tortoise to right itself. Terrains with severe slopes that would put the tortoise off balance enough to roll can predict where a tortoise is likely to be upended. Thus, terrains with vertical elements might be especially avoided by tortoises. Studying route choice differences would be one method to determine navigational differences between turtles and tortoises, as well as determining distance perception differences or capacities of their visual systems to perceive various angular surfaces differentially in the environment. For example, conditioning the organisms to respond to the longer of two lines and then showing them equivalent lines at different angles while recording their responses would allow researchers to determine angular preference and detection of distance differences in these reptiles.

Evolved navigation theory is a tool for looking at the full range of navigational costs in a way that integrates knowledge from other areas of science. Benefits of using ENT include its ability to account for both energetic costs and the costs of injury present in navigation, unlike foreshortening of receding horizontals and gravity theory. Evolved navigation theory also does not require unlikely computational or storage capacities demanded by affordance, since natural selection can shape mechanisms that need not understand the purpose of the behavior in order to accomplish the behavior. Indeed, ENT emphasizes a major component that is absent from other theories, but one that is essential to the study of biological systems—that the underlying purpose ultimately shaping all biological systems is gene propagation (Dawkins, 1976). Because ENT places navigational mechanisms in their evolved contexts, it facilitates a seamless integration of psychological processes with other areas of science, such as biology and physical anthropology.

The contributions of ENT are not mutually exclusive with all other approaches to visual perception, such as probabilistic explanations focusing on scene geometry (see Yang & Purves, 2003). However, using a framework such as ENT likely provides more empirically testable implications than just investigating behavioral mechanisms because ENT is a causal theory. Understanding why a behavior exists provides more implications in more areas than understanding how a behavior is generated.

In order for ENT to be useful, we must be able to narrow down a single implication that we can test empirically. Manageable implications of ENT include any one of the costs of navigation, such as energy costs or any of the specific injury risks.

I chose to investigate the navigation cost of falling for the following experiments due to its importance in navigation, likely perceptual response, and importance of such work in both applied and basic research. Thus, I pose my research question as follows, which was primarily motivated by ENT.

Are Some Perceptual Mechanisms Designed to Help Humans Avoid the Costs of Falling?

The navigation cost of falling is a risk for species that both possess some minimum body mass and encounter surfaces with falling costs. An organism's mass must be large enough such that their own weight, accelerated by gravity, causes significant injury during a fall. Additionally, a species must encounter surfaces from which its members could fall to injury regularly enough over evolutionary time for falling to pose selection pressure. These prerequisites exclude most non-animal species, invertebrate animals, and most aquatic and avian chordates.

Injuries from falling likely influenced reproductive fitness in all environments in which distinctly human ancestors evolved, as well as most terrestrial pre-human ancestors. Common injuries from a fall range from cuts to organ rupture and death. Such consequences pose nontrivial risks to health and life, even with safety equipment and modern medical intervention in technologically advanced areas. Falls less than two meters, especially unplanned falls, routinely cause serious injuries. In a planned fall, humans tend to face the direction of the fall and place their feet underneath their body. In an unplanned fall, humans usually face the vertical surface and are unable to use their limbs to ease the fall effectively. Unplanned falls often result in landing on the back and head without using arms or legs to catch oneself effectively. Falling uncontrollably onto one’s back and head is a distinct health risk at all heights, although poses greater risks at increasingly greater heights.

Perceptual mechanisms are important candidates for providing falling cost avoidance. Compared to higher-order mechanisms, perceptual mechanisms may affect navigational decisions both faster and with fewer cognitive resources, certainly more so than conscious decision. Perceptual mechanisms require little judgment, and thus little need for learning in trials that are life threatening.

Perceptual mechanisms make especially promising candidates for falling cost avoidance adaptations for two important reasons: 1) falling costs are easily perceived, and 2) a likely perceptual mechanism already exists for weighing navigational choices.

The primary source of falling costs is surfaces with vertical components and most terrestrial vertebrates can easily detect vertical surfaces. Falls result from initially being positioned higher than a nearby surface. Such height differences in the environment vary from gradual slopes to truly vertical surfaces or overhangs, all of which are easily detected by the visual systems of organisms who would suffer falling costs: terrestrial vertebrates.

In addition to easy perceptual detection of falling costs, there is also a perceptual candidate for integrating navigation cost into navigational choices: differential distance estimation. Organisms tend to pursue the nearest of otherwise equivalent navigational goals (Somervill & Somervill, 1977). This preference for nearer goals provides a mechanism for weighting navigational decisions based on navigational cost wherein overestimated distances would be pursued less than correctly estimated or underestimated distances.

If verticality poses falling costs and if organisms avoid overestimated distances, then we might consider that vertical surfaces could appear longer than horizontal ones. This is the focus of the current research.

A Problem and Predictions for Determining Verticality

A previous investigation of ENT-derived predictions demonstrated that participants unknowingly overestimated vertical surface length at a magnitude corresponding to the potential falling risk (Jackson & Cormack, in press). However, many surfaces cast images that are oriented vertically in respect to the observer's head or eyes (i.e. *egocentrically* vertical)—including surfaces with trivial falling risk. For example, looking down at the distance from one's feet to a distant point ahead on horizontal ground casts an egocentrically vertical image on the retina, yet poses negligible falling risk. Although we commonly assume that the retinal image largely determines perceived distance (Avraamides, Loomis, Klatzky, & Golledge, 2004; Foley, Ribeiro-Filho, & Da Silva, 2004; Wu, Ooi, & He, 2004), it obviously does not predict falling costs accurately.

The feature that does predict falling cost is environmental, or *exocentric*, verticality: the extent to which a surface parallels the direction of the earth's gravitational force. In order for the vertical overestimation derived from ENT to result in appropriate falling cost avoidance, vertical overestimation should exaggerate exocentrically vertical surface length, with little regard for egocentric verticality. If exocentric vertical overestimation occurs, its magnitude might increase with length of the vertical surface. Longer vertical surfaces pose greater falling costs, because they present a risk of longer falls, and greater falling risks, because they require more time to navigate them.

I addressed these questions in Study 1 by comparing real-world distance estimates across effectively equal egocentric images that nonetheless had different exocentric orientations corresponding to very different falling costs. In effect, participants estimated distances that were equal in length and roughly equal on the retina, but had different environmental orientations (either horizontal or vertical). I predicted from ENT that participants would overestimate distance only from exocentrically vertical surfaces because such surfaces posed distinct falling costs over evolutionary time.

I also varied stimulus length in the current study, which I predicted could affect the hypothesized overestimation in one of two ways. First, participants might overestimate by a constant percentage of the stimulus length (i.e. Weber's Law) because such a simple algorithm might provide sufficient falling cost avoidance. Alternatively, participants might overestimate by an ever-greater magnitude as stimulus length increases because longer vertical surfaces pose both greater costs and risks of falling. Such an algorithm would still function simply, likely needing input only on surface length and orientation to reduce falling costs suggested under ENT.

Study 1: Physical Reality

Methods 1

One hundred eighty-one introductory psychology participants met a research assistant (RA) in a campus laboratory and then proceeded to an outdoor testing site for distance estimation. Participants then returned to the office to complete a questionnaire.

Procedure

Participants viewed exocentrically vertical distances by looking ahead while standing on the ground, and estimated exocentrically horizontal distances by looking down while standing at a height (see Figure 1). Participants gave distance estimates by telling the RA where to move a green laser dot. Participants essentially made an imaginary letter ‘L’ from three dots where the ‘L’ had segments of equal length. Participants adjusted each egocentrically horizontal distance via method of adjustment until its length appeared equal to the egocentrically vertical distance. Participants received as much time, and could make as many adjustments, as they liked. The RA then determined the distance estimated by viewing high-resolution photographs of the estimated surface with superimposed distances.

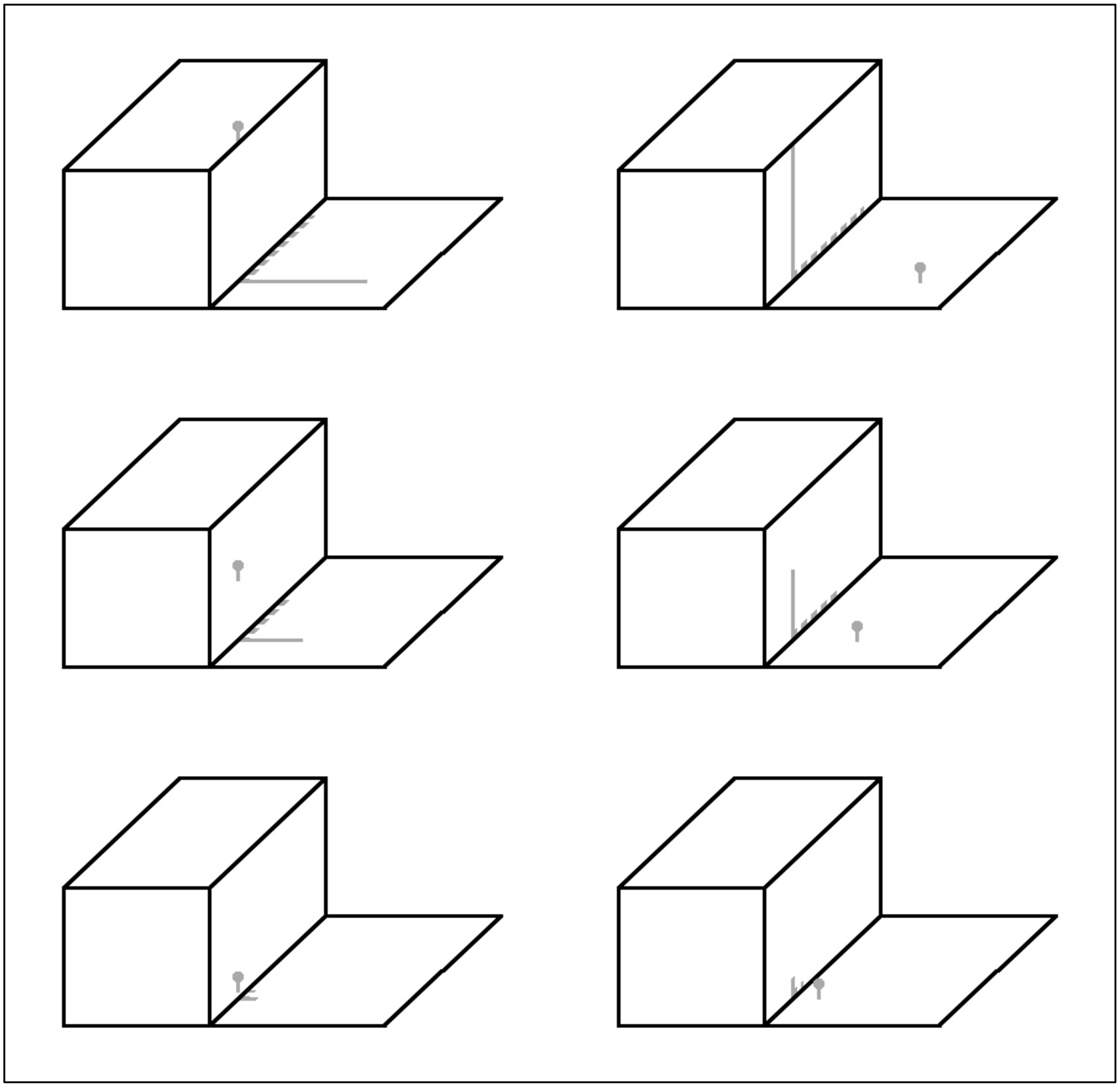


Figure 1. Observer (dotted icon) position during six estimates. Solid grey lines denote the distance to estimate, dashed lines denote the path of estimation. Exocentrically horizontal estimates appear in the left column, vertical in the right column. Long distance (14.39 m) appears in the top row, medium (8.37 m) in the middle, and short (2.35 m) in the bottom. Not to scale.

In order to study this phenomenon in an ecologically valid outdoor setting with rich stimuli, I modeled procedures after similar previous research. In Chapanis and Mankin's 1967 research on the vertical-horizontal illusion in a realistic setting, they had participants direct an experimenter to move out at a right angle from a vertical surface until the distance looked equal to the height of the vertical surface. Yang, Dixon, and Proffitt (1999) also used this procedure in their work on distance estimation differences between reality and photographs. In other work on the vertical-horizontal illusion in realistic settings, Higashiyama (1996) had participants adjust the distance from themselves to a wall until that distance appeared equal to the wall's height. In work on the descent illusion, Jackson and Cormack (in press) had participants in one experiment direct an experimenter to move away from a wall until the distance appeared equal to the height of a building. The current experimental predictions relied on estimation differences across positions, yet estimation method was invariant across estimates.

Stimuli

Participants estimated exocentrically vertical distances on a parking garage while standing in an adjoining parking lot and estimated exocentrically horizontal distances in the parking lot while standing at various heights on the parking garage (see Figure 1). Participants estimated three stimulus distances (long: 14.39 m, medium: 8.37 m, and short: 2.35 m) in both exocentric orientations, constituting six estimates per participant. Vertical distances were large enough to inflict falling costs and all participant positions were not impassably obstructed, such as with a window or screen.

Distance from participant to the stimulus surface was equal across both exocentric orientations within all three stimulus lengths. The distance being estimated was equal to the distance from the participant to the surface being estimated. I also added 30 cm to the distance from the participant to the vertical surface during exocentrically vertical estimates because estimates of the exocentrically horizontal surfaces positioned participants eyes above the railing of the parking garage by an average of 30 cm. For example, when estimating the long exocentrically vertical stimulus, participants stood 14.39 m away from the vertical surface, plus 30 cm to account for the distance that participants' eyes extended above the vertical surface during estimates of the horizontal stimulus. Participant positions were identical between subjects and each estimate occurred at a different lateral position so that participants would not estimate a distance on which they had previously stood. I randomized stimulus order between vertical- v. horizontal-first, and long- v. short-first in both vertical and horizontal estimates with roughly equal numbers of participants of both sexes in every order condition.

Questionnaire

Participants completed a short questionnaire in the lab after estimating the outdoor distances. The questionnaire consisted of demographic questions and questions concerning climbing and falling experiences (see Appendix A). The experiential questions, ordered for clarity, were as follows:

1) Do you fear heights? (Not at all; Slightly; Moderately; Very much; Intense, possibly irrational, fear)

2) As a child, how often did you climb things, like monkey bars, trees, or jungle gyms? (Never, Rarely, Occasionally, Frequently, All the time)

3) How often do you climb things now? This could be anything vertical, like ladders, trees, or rocks. (Never, Rarely, Occasionally, Frequently, All the time)

4) Do you have any indoor rock-climbing wall experience? (No experience, Some experience, Climb occasionally, Climb regularly, Expert)

5) Do you have any outdoor rock-climbing experience? (No experience, Some experience, Climb occasionally, Climb regularly, Expert)

6) Do you have any aircraft piloting experience? (No experience, Some experience, Pilot occasionally, Pilot regularly, Expert)

7) Have you ever been injured from a fall? (Yes, No (skip to the end))

8) If yes, how many times?

9) If yes, how badly were you hurt on the worst occasion? (Barely [like a small scrape], Somewhat [like a large scrape or cut], Significantly [something requiring a doctor's attention], Severely [required hospitalization or a trip to the emergency room], At risk of death [required prolonged hospital stay and possibly physical rehabilitation])

Participants also completed a standard ‘L’ format vertical-horizontal illusion task. For this task, participants sat at a table and drew a horizontal line at the bottom of a 9.1 cm vertical line on a standard sheet of paper until the two lines appeared equal in length. Participants received as much time, and could make as many adjustments, as they liked. I hypothesized that this classical illusion could be a two-dimensional (2D) byproduct of adaptations designed to estimate three-dimensional (3D) surfaces and so might correlate with participants' outdoor vertical distance estimates.

Results 1

Figure 2 illustrates the primary finding: participants estimated exocentrically vertical distances differently than exocentrically horizontal distances. Participants overestimated only exocentrically vertical distances. Participants overestimated exocentrically vertical distances to a large, increasing degree as stimulus length increased. Participants underestimated exocentrically horizontal distances to a slight, constant degree that parallels accuracy across distances.

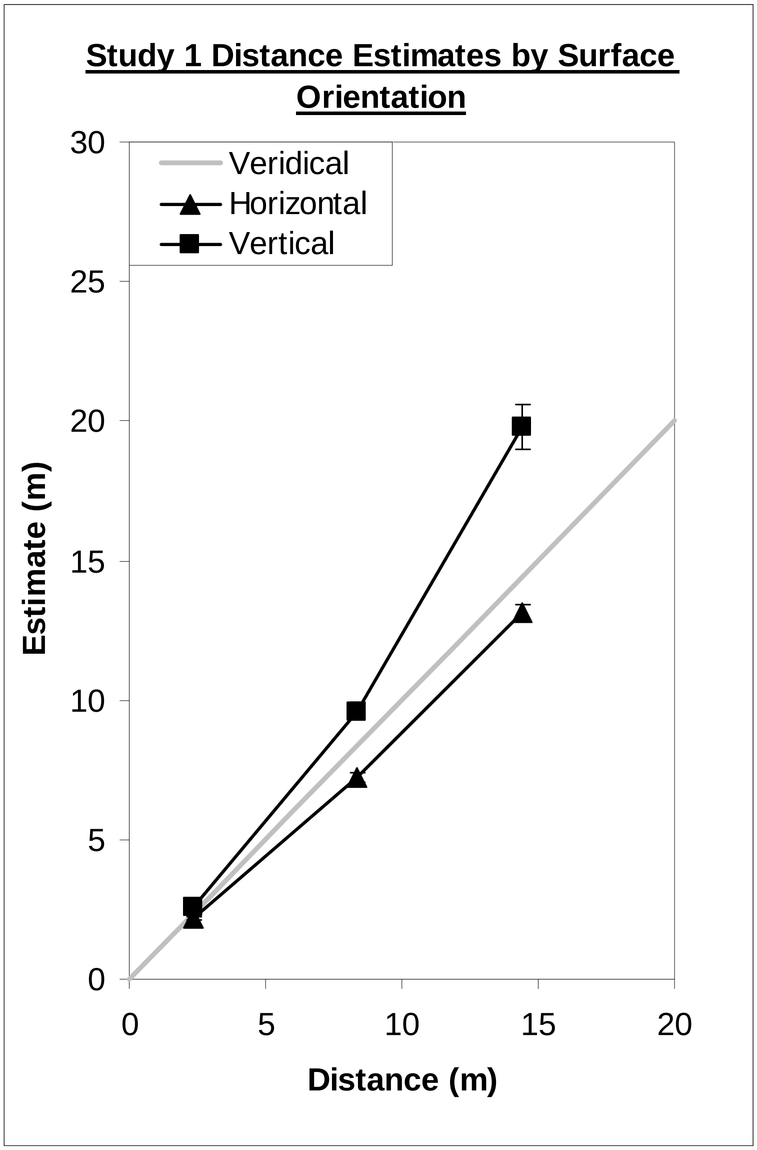


Figure 2. Study 1 mean distance estimates by stimulus length in meters. Grey line indicates performing accurate estimation, triangles indicate observed estimates of exocentrically horizontal surfaces, and squares indicate observed estimates of exocentrically vertical surfaces. Error bars show 95% confidence intervals about the means. Some error bars are too small to be visible, but all appear in Table 1.

All six estimates significantly differ from both accuracy (the *least* significant of which: t (180) = 6.261, $p < .001$), and one another within distance (the *least* significant of which: t (180) = 10.998, $p < .001$). Table 1 displays descriptive statistics and comparisons between estimates with 95% confidence intervals around means.

Figure 3 and the rightmost column in Table 1 display illusion magnitude with 95% confidence intervals around the means. Illusion magnitude equals mean vertical estimate, divided by mean horizontal estimate, minus 100%; i.e. vertical extent estimated that exceeds the horizontal estimate. The corresponding confidence intervals account for error propagation found in values composed of ratios of two means (Bevington & Robinson, 1992, p. 40-51; Motulsky, 1995, p. 285-286). Illusion magnitude increased with stimulus length from 17% at short distances to 51% at long distances. Compared to average magnitude (34%), this does not appear to reflect Weber's constant, but may reflect Steven's Law within the range of distances estimated here.

Table 1

Study 1 Descriptive Statistics and Difference Scores for Six Distance Estimates in Meters

Stimulus length	Exocentric orientation	Estimate (95% CI)	Over / under-estimate	Orientation difference	Correlation within length (*p*-value)	Illusion magnitude (95% CI)
Short (2.35)	Horizontal	2.18 ± 0.04	-0.17	0.38	.249 (.001)	17.4 % ± 3.7 %
	Vertical	2.56 ± 0.07	0.21			
Medium (8.37)	Horizontal	7.23 ± 0.17	-1.14	2.36	.376 (<.001)	32.5 % ± 5.3 %
	Vertical	9.59 ± 0.31	1.22			
Long (14.39)	Horizontal	13.14 ± 0.28	-1.25	6.66	.224 (.002)	50.6 % ± 7.0 %
	Vertical	19.80 ± 0.82	5.41			

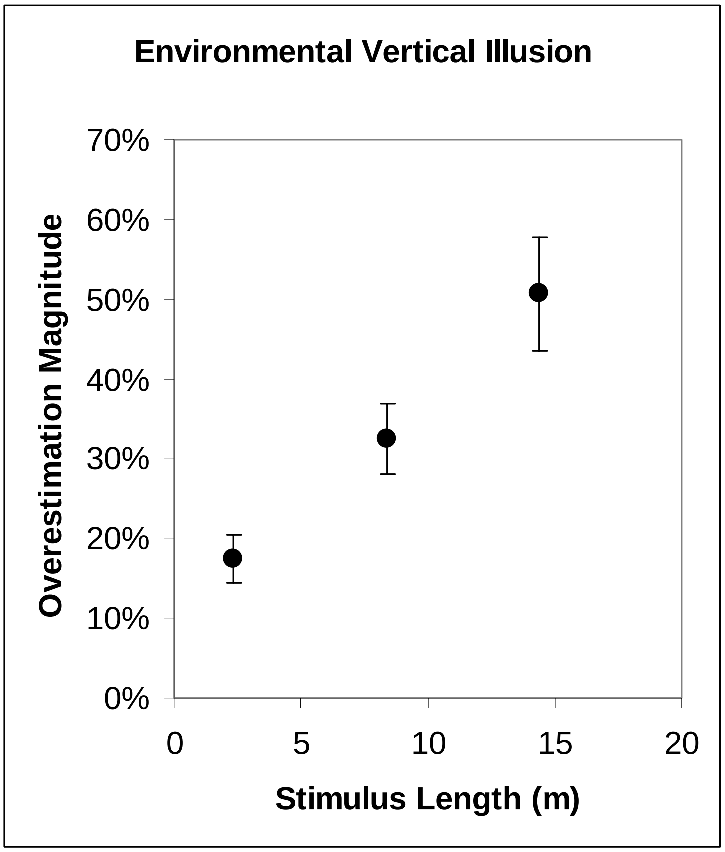


Figure 3. Environmental vertical illusion magnitude by stimulus length in meters. Error bars show 95% confidence intervals about the means.

Additional Analyses

Order, sex, and body height.

The order of estimates (i.e. estimating exocentrically vertical surfaces before horizontal ones or vice versa) may have influenced distance estimates, but in a trivial manner in respect to the experimental predictions. Participants who first estimated vertical surfaces tended to have larger differences between their vertical and horizontal estimates at the medium (t (179) = 3.359, p = .001) and short (t (179) = 2.912, p = .004) distances than those who first estimated horizontal distances. Although these differences are *statistically* significant, participants who started with either vertical or horizontal estimates still overestimated vertical surfaces and not horizontal surfaces, on average, at every distance. The average difference between horizontal and vertical estimates at the short and medium distances for those starting with vertical surfaces (short: 0.30 m, medium: 2.81 m) compared to those starting with horizontal surfaces (short: 0.42 m, medium: 2.07 m) are very small and show no trend across exocentric orientation.

Similarly, female participants' average estimate differences across orientations at the long distance were larger than men's average estimates (t (179) = 2.043, p = .043); however, both sexes overestimated vertical distances only.

Participant body height failed to correlate with any of the six distance estimates or with estimate difference scores between orientations (the *most* significant of which: r (179) = - .118, p = .112).

Vertical-horizontal illusion.

The last 141 participants sufficiently completed the VHI test, which was still sufficient to determine VHI effects. Average horizontal estimate of the 9.10 cm vertical line in the VHI was 9.48 ± 0.11 cm (95% C.I.), or a 4.2 % vertical overestimation. The current mean estimate is also highly similar to those of previous VHI research that used similar methods, which found vertical overestimations from 2.9 to 7.1% (Avery & Day, 1969; Bolton, Michelson, Wilde, & Bolton, 1975; Künnapas, 1957a; Künnapas, 1957b; Künnapas, 1958; Raudsepp, 2002).

VHI estimates correlated with vertical distance estimates at the medium (r (139) = .252, p = .003) and short (r (139) = .281, p = .001) distances and correlated, to a lesser degree, with horizontal estimates at the long (r (139) = .188, p = .025) and short (r (139) = .182, p = .031) distances. Average VHI correlation across all six distances, including correlations where p > .05, equalled .174. VHI estimates nearly significantly correlated with illusion magnitude only at the medium distance (r (139) = .169, p = .045) and failed to significantly correlate with average illusion magnitude within subject (r (139) = .054, p = .527).

Experience questionnaire.

The first six experiential questions (fear, piloting, and climbing experience) correlated with distance estimates only once (out of 36 possible correlations): between outdoor climbing experience and short horizontal distance estimates (r (179) = .170, p = .022). Considering the Type I error rate inflation from so many comparisons, it is unlikely that this relationship is reliable.

Among the experiential questions concerning injury (questions 7-9), 55 participants reported previous injury from a fall. Previous falling injury did not correspond to different distance estimates or difference scores between orientations (the *most* significant of which: t (179) = 1.563, p = .120). However, among those reporting falling injuries, severity of worst injury correlated (inversely) with estimates of vertical surfaces at the medium (r (53) = -.377, p = .005) and short (r (53) = -.342, p = .011) distances, as well as difference scores between vertical and horizontal estimates at the medium (r (53) = -.311, p = .021) and short distances (r (53) = -.305, p = .024).

Importantly, two individuals reported 200 injuries, while the remainder reported no more than 20. Removing these two extreme scores still yields significant inverse correlations between injury severity and vertical distance estimates at the medium (r (51) = -.364, p = .007) and short (r (51) = -.352, p = .010) distances, as well as significant inverse correlations with difference scores between vertical and horizontal estimates at the medium (r (51) = -.302, p = .028) and short (r (51) = -.299, p = .030) distances.

Figure 4 displays illusion magnitude by previous injury severity with 95% confidence intervals around the means. Confidence intervals account for error propagation found in values composed of ratios of two means (Bevington & Robinson, 1992, p. 40-51; Motulsky, 1995, p. 285-286) and are not present at a level '5' injury because it was experienced by only one participant.

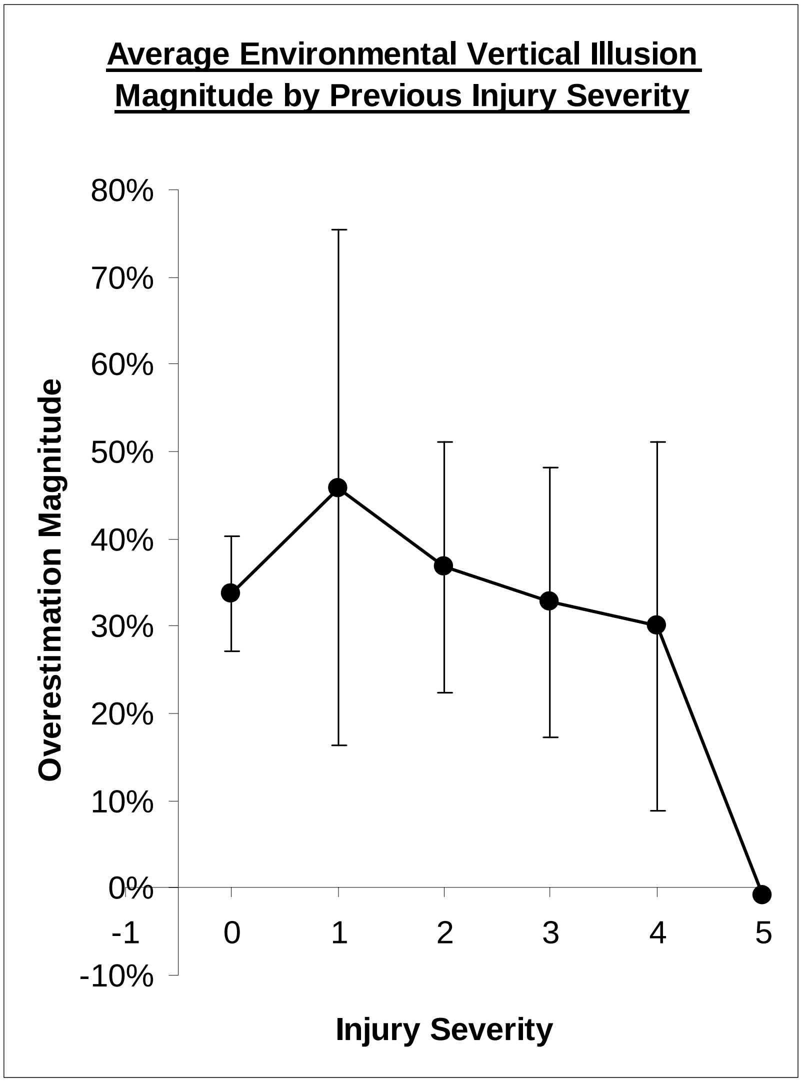


Figure 4. Environmental vertical illusion magnitude by severity of worst previous falling injury. Error bars show 95% confidence intervals about the means. Level 5 injury was experienced by only one participant.

Discussion 1

As predicted from ENT, participants overestimated exocentrically vertical distances and did not overestimate exocentrically horizontal distances—despite actual distances being equal across both orientations and despite egocentric orientation and image size being highly similar. I title this the *Environmental Vertical Illusion*.

I found the environmental vertical illusion at a very large magnitude for a previously unknown psychological process that likely occurs constantly throughout everyday activity. The 51% environmental vertical illusion magnitude at the long stimulus corresponds to vertical overestimates 6.5 m greater than horizontal estimates of a 14.4 m stimulus. This is roughly equivalent to estimating the height of a five-story building when the equivalent length perceived on the ground is equal to that of a school bus. Greater illusion magnitudes associated with longer stimuli may reflect both increased probability and severity of falling costs from longer vertical surfaces.

The relatively constant, slight underestimation of exocentrically horizontal surfaces averaged 9.8 % and may have resulted from a texture discontinuity only present in horizontal estimates. Horizontal stimuli spanned grass, cement, and asphalt, while the surface on which participants estimated spanned only grass. Feria, Braunstein, and Andersen (2003) found texture discontinuities resulting in 5% average underestimation while Sinai, Ooi, and He (1998) found an average of 4% underestimation across discontinuous cement-grass surfaces; however, both studies used distances much shorter than those used in the current study. The texture discontinuity in the current study was most prominent at the medium and long horizontal stimulus lengths, possibly reflected in participants' estimates.

The constant, slight underestimation of the exocentrically horizontal distance may have also indicated an anchoring effect in the conservative measurement techniques. Previous unrelated pilot study participants made seemingly shorter estimates when the distance indicator started at a point shorter than the true stimulus distance, but made longer estimates when the indicator started at a point longer than the true distance. Other distance estimation researchers have found such an anchoring effect (Mankin, 1969; Taylor, 1961). I chose to start the laser dot at the shortest distance (i.e. 0 m) in this study in order to be conservative against the predictions. More importantly, this method was necessary in order to reduce tedium, as participants would have otherwise had to tell, and then wait for, the research assistant to move the laser dot in from 60 m in order to estimate distances of only 14, 8, and 2 m. If the current horizontal distance estimates were subject to an anchoring effect, then they would likely be closer to accuracy without it. The observed vertical overestimates, measured via the same methods, would likely be even larger as well.

Additional Findings

Order, sex, and body height.

Testing order, sex, and body height did not appear to affect distance estimates in any important way. Evolved Navigation Theory would suggest that these factors should affect distance estimation insofar as they predict differential navigational costs over evolutionary time and no such differences are apparent.

Vertical-horizontal illusion.

VHI estimates correlated with some estimates of both horizontal and vertical distances. These data may support the hypothesis that the VHI is a 2D byproduct of mechanisms designed for 3D navigation.

Although VHI correlation with vertical estimates was promising, the correlation, even at a smaller magnitude, with horizontal estimates argues against the VHI being specific to falling costs in 3D navigation. The lack of clear evidence requires additional investigation before concluding that the VHI measures any specific 3D mechanism. A follow-up design that I plan to conduct is to test the VHI while orienting the paper both at the ubiquitous horizontal orientation on a table, but also at a vertical orientation, such as on a wall. Due to the impoverished nature of the VHI stimulus, prompting participants with different orientations may further engage different distance estimation mechanisms.

Experience questionnaire.

Fear, piloting, and climbing experience did not appear to affect distance estimates. The most obvious reason for this could be that these variables do not actually gauge the cognitive mechanisms involved in distance estimation. However, with piloting, there were too few participants with any experience (7) for there to be sufficient power to determine the effects of piloting. For all of these variables, it would be preferable in the future to gauge them with more objective and continuous behavioral measures, instead of categorical self-reports. This could entail heart rate and skin conductance indices for fear, or climbing competency tests for climbing experience.

Nonetheless, it is interesting that severity of previous fall injury corresponds to significantly less overestimation of short and medium vertical surfaces. If vertical overestimation helps humans avoid falling costs, it may be that direct experience with incurring those costs attenuates vertical distance estimation mechanisms by moving them closer to objective reality. If true, it could mean that previously injured participants did not attenuate estimates of the longest vertical distances because they either have not fallen from long distances, or because falling from longer vertical distances produces outcomes, such as death, that make individuals unlikely to be in this sample. It could also mean that longer vertical surfaces pose such high risk that no amount of experience would be helpful to reduce their costs.

These data on a direct relationship between vertical distance estimation and falling costs are very valuable. Although one can argue that '*because* vertical surfaces more likely produce falls, *and* overestimation produces navigational avoidance, then overestimation of vertical surfaces *could* lead to lower falling costs,' such reasoning only indirectly suggests that falling costs explicitly are major components of vertical overestimation. It is much more compelling that vertical distance estimation is importantly determined by potential falling costs when reported falling injuries correlate only with vertical estimates. This goes against the dominant, nearly ubiquitous, approach in perceptual science that visual cues alone determine distance estimation, which is neither dependent on navigation cost, nor specialized to different environmental orientations (Avraamides, Loomis, Klatzky, & Golledge, 2004; Foley, Ribeiro-Filho, & Da Silva, 2004; Wu, Ooi, & He, 2004).

A study to answer further questions about the effects of injury on height estimation would benefit from data on distance of previous fall that produced the specific injury. While self-report data would be convenient, participants' memories of a height could be subject to the illusions reported here (which would be an interesting study on its own). Objective measures of the vertical distance that produced the fall might be obtained via hospital records. It might also be possible to follow up on mountaineering accident reports published annually in Accidents in North American Mountaineering in order to see if longer falls produce decreased overestimation of longer distances.

Further studies could benefit from using continuous, instead of categorical, injury severity indices. It would also be interesting to determine if injuries to certain parts of the body affect distance estimation more than injury to other parts. I would additionally like to gather data on time since most recent falling injury and time since most severe falling injury in order to investigate temporal aspects of height estimation. The duration of the injury, such as how long it took to regain pre-injury usage, might delineate the effects of injuries on height estimation.

This research may suggest that height estimation defaults to a very large magnitude overestimation until one gains more experience with the navigation costs associated with vertical surfaces, at which time the overestimation magnitude decreases, but does not disappear. If this is true, it could help us understand the currently unknown cause of acrophobia.

Individuals with acrophobia tend to have *less* experience with their phobia target, which is different from other specific phobias. It is interesting that those with the greatest fear of vertical navigation costs have the least experience with suffering those costs. The current research may suggest that acrophobics may not be best characterized solely by a pronounced fear of heights, but possibly by a more normal fear response to an exaggerated perception of the height. It would be useful in future studies to gauge participant acrophobia.

Study 2: Virtual Reality

Space constraints, especially with distance matching methods, often rule out many environmental distance estimation procedures. Furthermore, no locale can offer easy access to all environmental features of interest in distance perception. Environments in physical reality can also prohibit some experimental control of stimuli. These elements make virtual reality methods important tools for perception researchers.

I designed Experiment 2 to investigate perceptual mechanisms found in physical reality with virtual reality methods. Participants estimated the same distances, with the same methods, in similar virtual environments, in the same positions, and at the same viewing angle and scene geometry as in Study 1 (see Figure 1).

Methods 2

One hundred and five randomly selected introductory psychology participants met an RA in a campus laboratory and made distance estimates on a head-mounted display (HMD). Participants then completed two questionnaires.

Apparatus

Research Assistants fitted participants with the HMD and insured that its adjustable headset was comfortable and that it displayed stimuli clearly throughout all procedures. I used a Virtual Research V8 HMD displaying a resolution of 640 x 480 at 60 Hz. The HMD accommodated glasses (10-30 mm from eye to HMD optics) and interpupillary distances from 52-74mm. The view was not sensitive to participant head orientation and RAs instructed participants when and where to point their heads as the view rotated.

Procedure

Virtual reality procedures replicated the physical reality procedures as closely as possible. Participants started with a short tour of the environment before estimating distances at each orientation (see Figure 1). Participants were given a roughly 30 second break after all estimates at the first orientation and then again received the same initial tour and proceeded to estimates at the remaining orientation. The order of vertical first or horizontal first was assigned randomly across participants, controlled for roughly equal numbers of participants of both sexes in both order conditions. At each orientation, participants received five trials of three estimates—one at each of three distances (2.35, 8.37, and 14.39 m). This resulted in thirty total estimates by every participant. Order of distance estimates was randomized within each trial. Participants received as much time, and could make as many adjustments, as they liked for every estimate.

Tour.

Participants began in a virtual field of grass while viewing a red brick wall on asphalt in the distance (see Figure 5 or Appendix B). With narration by the RA, the view moved to the edge of the asphalt and then participants were instructed to rotate their heads up as the view rotated to a point at the top of the wall, and then rotated back down to level. The view then moved close to the wall and rotated up with participants' heads to point at the top of the wall, then rotated back down.

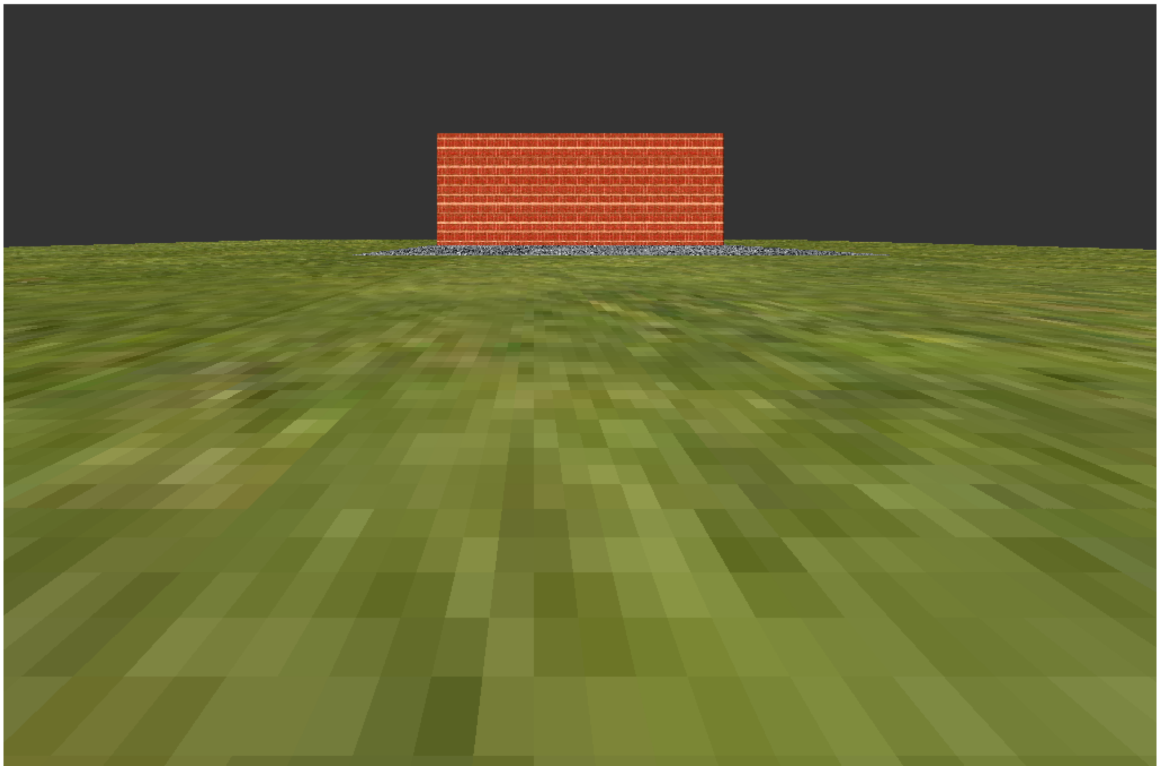


Figure 5. Participant view at the beginning of the virtual reality tour in Study 2. See Appendix B for larger additional views.

Exocentrically vertical distance estimates.

Vertical estimates began immediately after a tour and consisted of moving the view back to 2.35, 8.37, or 14.39 virtual meters from the wall, plus 30 cm to equate views to Study 1. Research assistants then directed participants to estimate the distance from a top dot at a fixed height on the wall to a bottom dot directly beneath it on the ground. The distance from the top to bottom dot was roughly equal to the distance from the participant to the wall, i.e. participants estimated a 14.39 m distance on the wall when they were positioned 14.39 m (plus 30 cm) from the wall.

Participants estimated each distance by telling the RA to move an indicator dot out or in from the bottom dot until the indicator appeared to be the same distance from the bottom dot as the bottom dot was from the top dot. Participants essentially made an imaginary letter ‘L’ out of three dots (see Figure 6 for one example or Appendix B). The indicator dot appeared in random initial locations both longer and shorter than the actual distance in order to control for anchoring effects.

Once participants completed an estimate, the view moved to any remaining distance until participants had estimated each of the three distances. The next trial of three distance estimates began seamlessly until participants completed five trials of three distance estimates apiece.

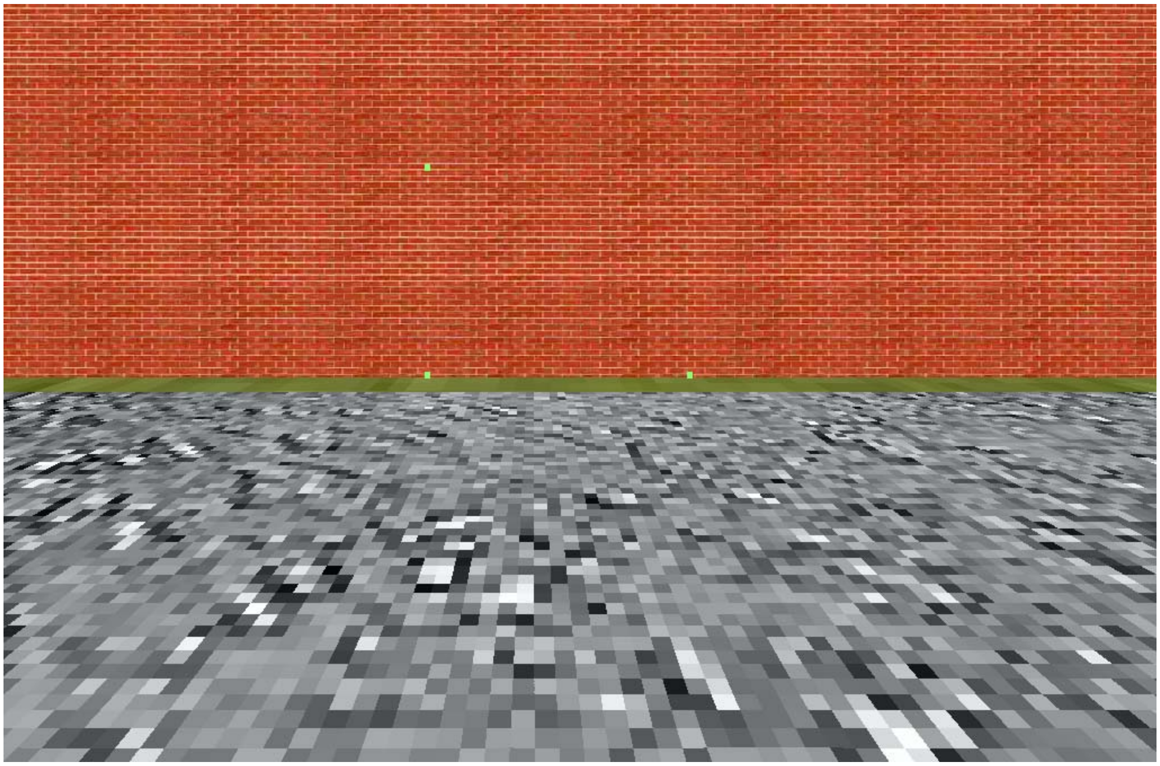


Figure 6. Participant view at the beginning of an estimate of the short exocentrically vertical distance in Study 2. See Appendix B for larger additional views.

Exocentrically horizontal distance estimates.

Horizontal estimates also began immediately after an initial tour. The view moved close to the wall and then turned around and rotated down with participants' heads to point at the ground. The view then moved up on the wall 2.35, 8.37, or 14.39 virtual meters from the ground, plus 30 cm to equate views to Study 1. Research assistants then directed participants to estimate the distance from a further dot out on the asphalt to a bottom dot at the base of the wall. The distance from the further to bottom dot was roughly equal to the distance from the participant to the ground, i.e. participants estimated a 14.39 m distance on the ground when they were positioned 14.39 m (plus 30 cm) from the ground.

Participants estimated each distance by telling the RA to move an indicator dot out or in from the bottom dot until the indicator appeared to be the same distance from the bottom dot as the bottom dot was from the further dot. Participants essentially made an imaginary letter 'L' out of three dots (see Figure 7 for one example or Appendix B). The indicator dot appeared in random initial locations both longer and shorter than the actual distance in order to control for anchoring effects.

Once participants completed an estimate, the view moved to any remaining distance until participants had estimated each of the three distances. The next trial of three distance estimates began seamlessly until participants completed five trials of three distance estimates apiece.

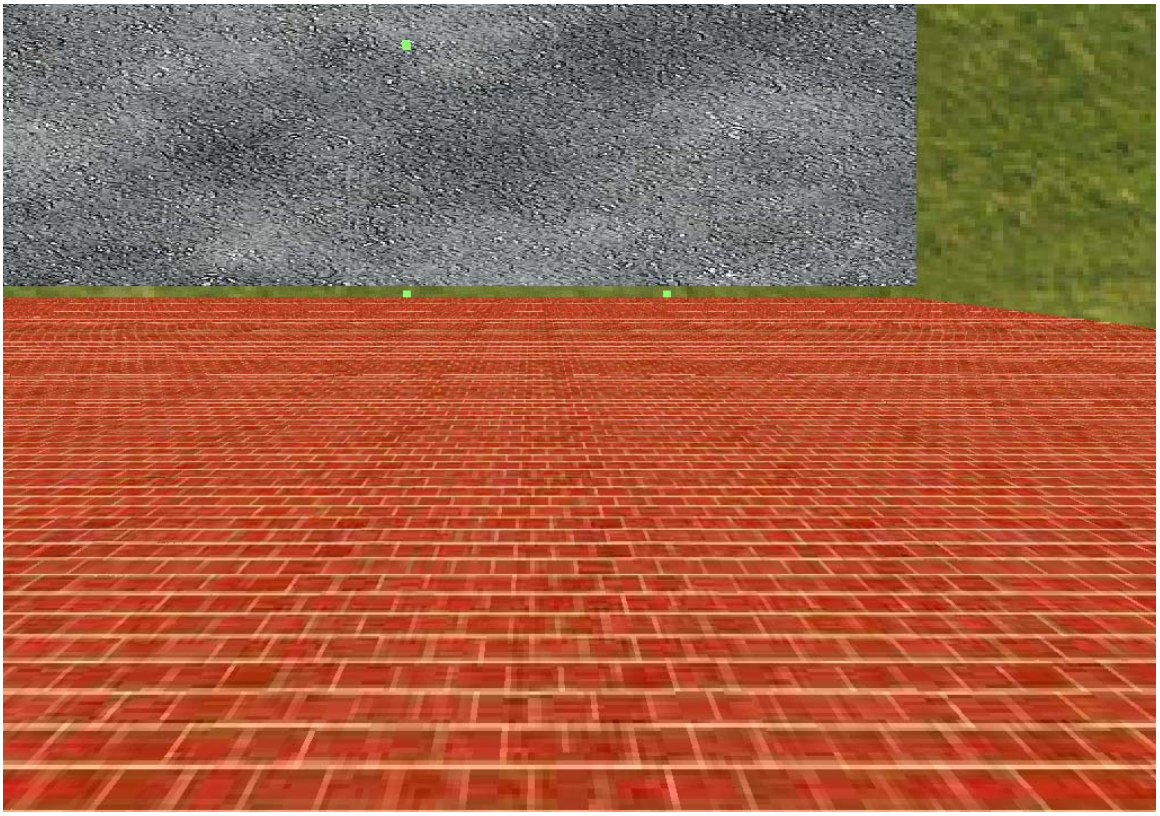


Figure 7. Participant view at the beginning of an estimate of the medium exocentrically horizontal distance in Study 2. See Appendix B for larger additional views.

Questionnaires

Participants completed the same VHI and questionnaire from Study 1 immediately after their virtual distance estimates. Participants also completed the Acrophobia Questionnaire, or ‘AQ’ (Cohen, 1977). This questionnaire is the primary clinical tool for diagnosing acrophobia and it contains twenty questions that measure anxiety and avoidance in response to experiences with heights (see Appendix C).

Results 2

Figure 8 illustrates the primary finding: participants estimated exocentrically vertical distances seemingly indistinguishably from exocentrically horizontal distances and likely estimated both surface distances indistinguishably from the actual distances.

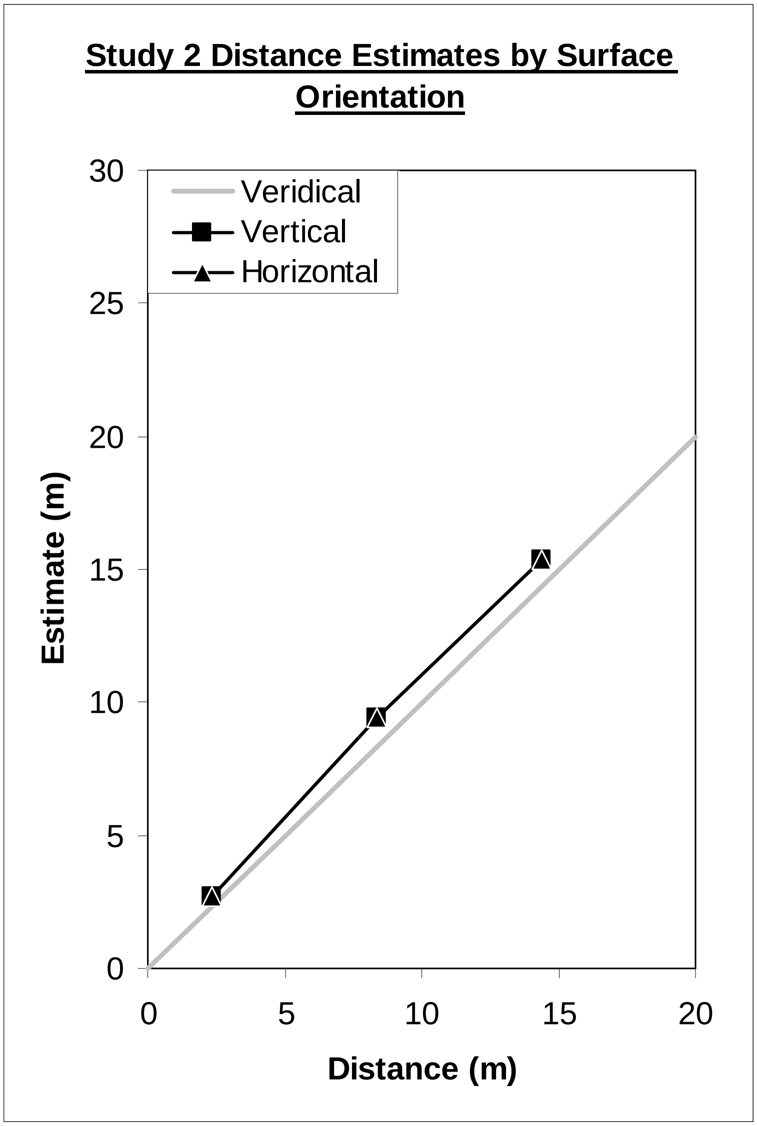


Figure 8. Study 2 mean distance estimates by stimulus length in meters. Grey line indicates performing accurate estimation, triangles indicate observed estimates of exocentrically horizontal surfaces, and squares indicate observed estimates of exocentrically vertical surfaces. Error bars show 95% confidence intervals about the means, but are too small to be visible. All means with confidence intervals appear in Table 2.

All six estimates differ statistically, but not importantly, from accuracy (the *least* significant of which: t (104) = 8.063, $p < .001$). Short and medium distance estimates differed from one another by orientation (short: t (104) = 3.333, $p = .001$, and medium: t (104) = 2.362, $p = .020$). The magnitude of all differences in these primary findings are very small and are more likely artifacts of the sample size, rather than indicators of underlying distance estimation differences. Table 2 displays descriptive statistics and comparisons between estimates with 95% confidence intervals around means.

Table 3 displays how learning or practice effects did not appear to affect estimates. No trend appeared across trials within any of the six estimates. The range of scores across all five trials composed no more than 4% of any mean estimate.

Table 2

Study 2 Descriptive Statistics and Difference Scores for Six Distance Estimates in Meters

Stimulus length	Exocentric orientation	Estimate (95% CI)	Over / under-estimate	Orientation difference	Correlation within length (*p*-value)
Short (2.35)	Horizontal	2.70 ± 0.04	0.35	0.06	.486 (<.001)
	Vertical	2.64 ± 0.03	0.29		
Medium (8.37)	Horizontal	9.40 ± 0.15	1.03	0.16	.570 (<.001)
	Vertical	9.24 ± 0.13	0.87		
Long (14.39)	Horizontal	15.37 ± 0.24	0.98	0.12	.664 (<.001)
	Vertical	15.49 ± 0.20	1.10		

Table 3

Study 2 Practice Effects: Distance Estimates Across Five Trials

	Exocentric Orientation and Stimulus Distance					
Estimate Order	Horizontal Long	Horizontal Medium	Horizontal Short	Vertical Long	Vertical Medium	Vertical Short
First	15.61	9.35	2.74	15.26	9.15	2.70
Second	15.41	9.48	2.69	15.39	9.27	2.59
Third	15.45	9.49	2.76	15.75	9.37	2.70
Fourth	15.66	9.48	2.68	15.78	9.28	2.64
Fifth	15.04	9.46	2.72	15.24	9.36	2.67
Average	15.43	9.45	2.72	15.48	9.29	2.66
Actual	14.39	8.37	2.35	14.39	8.37	2.35
Range/Mean	0.04	0.02	0.03	0.03	0.02	0.04

Additional Analyses

Order, sex, and body height.

The order of estimates (i.e. estimating exocentrically vertical surfaces before horizontal ones or vice versa) may have influenced distance estimates, but in a trivial manner in respect to the experimental predictions. Participants who first estimated vertical surfaces tended to have larger differences between their vertical and horizontal estimates at the short (t (103) = 2.683, p = .009) distance. Although these differences are *statistically* significant, the actual difference was less than 10 cm.

Participant sex did not significantly alter distance estimate differences by orientation at any distance (the *most* significant of which t (103) = 1.535, p = 0.128).

Participant body height also failed to correlate with any of the six distance estimates and failed to correlate with estimate difference scores between orientations (the *most* significant of which: r (103) = .091, p = .357).

Vertical-horizontal illusion.

Average horizontal estimate of the 9.10 cm vertical line in the VHI was 9.45 ± 0.13 cm (95% C.I.), or a 3.9 % vertical overestimation. This result is highly similar to the identical VHI task in Study 1 that featured an average VHI of 4.2%. The current mean estimate is also highly similar to those of previous VHI research that used similar methods, which found vertical overestimations from 2.9 to 7.1% (Avery & Day, 1969; Bolton, Michelson, Wilde, & Bolton, 1975; Künnapas, 1957a; Künnapas, 1957b; Künnapas, 1958; Raudsepp, 2002).

VHI estimates correlated with all distance estimates, ranging in significance from r (103) = .270 (p = .005) at the short horizontal estimate to r (103) = .350 (p < .001) at the short vertical estimate. Average correlation of VHI across all six distance estimates was .332.

Experience questionnaire.

Only one experiential question correlated with statistical significance with any distance estimate. Estimates of medium horizontal surfaces correlated with question three—how often participants climb now (r (103) = .216, p = .027). Considering the Type I error rate inflation from so many (54) comparisons, it is unlikely that this one relationship is reliable.

No experiential question correlated with VHI estimates (the *most* significant of which r (102) = -.131, p = .185). Whether or not a participant had previously fallen to injury failed to relate significantly to any distance estimate (the *most* significant of which t (103) = 1.588, p = .115).

Acrophobia questionnaire.

The eighth AQ question (cross-country flight) correlated with medium horizontal estimates (r (103) = -.236, p = .016) and the tenth AQ question (walking on a highway bridge) correlated with medium vertical estimates (r (103) = .219, p = .025). However, given the high number (120) of correlations, and given that these two correlations do not uniformly suggest similar conclusions, it is unlikely that they indicate a more than chance occurrence.

Estimates of the long vertical surfaces, however, correlated with AQ items 9, 10, 17, and 20, ranging from r (103) = .199 (p = .042) to r (103) = .251 (p = .010). The number of AQ items that correlated with this single estimate appears to suggest that greater anxiety with heights may predict larger estimates of large virtual vertical surfaces.

VHI estimates failed to correlate with any of the twenty AQ items (the *most* significant of which r (103) = -.174, p = .076).

Discussion 2

Mean virtual reality distance estimates vary indistinguishably from the actual distances. This suggests that participants, as a group, estimated accurately both vertical and horizontal distances. These virtual reality methods failed to replicate the environmental vertical illusion observed outdoors in Study 1.

The current virtual reality study also failed to replicate vertical overestimation observed in previous work (Chapanis & Mankin, 1967; Higashiyama, 1996; Higashiyama & Ueyama, 1988; Yang, Dixon, & Proffitt, 1999), while Study 1 did replicate these findings. Other research in which falling costs were manipulated also supports the results of the outdoor experiment in Study 1 (Jackson & Cormack, in press). These points suggest that results of the virtual reality study are less indicative of human distance estimation in 3D settings than the results of Study 1.

If the virtual reality results of Study 2 failed to replicate previous findings in realistic settings, then the methods likely did not produce a perception of reality in important ways. If these virtual methods did not suggest reality to participants, then participants likely did not have the impression of falling risks associated with the vertical surfaces that they estimated. It is interesting that participants did not overestimate surfaces from which they did not perceive realistic falling costs. I predicted from ENT that participants would overestimate surfaces with specific navigation costs. It appears that, even within vertical surfaces, participants only overestimate surfaces realistically associated with falling.

Differences between VHI correlations and distance estimates across the two studies further suggests that different distance estimation mechanisms were used between the two studies. Participants estimated environmentally vertical surfaces more independently across orientation in Study 1 than Study 2. Correlations across orientation were significantly higher in Study 2 than in Study 1 at each distance: short ($z = 2.327$, $p = .010$) medium ($z = 2.037$, $p = .021$) and long ($z = 4.598$, $p < .001$).

One of the most obvious differences between the virtual reality methods and realistic distance estimation is that the visual scene was insensitive to head movement. Such a scenario occurs in important applied settings. Distance estimation without head movements tied to scene change occurs in piloting the multi-billion dollar Mars Rovers, piloting military and research drone aircraft (such as the Predator or Raven currently flown by the U.S. in Iraq and Afghanistan), and during scopic surgery. All of these tasks involve viewing a stationary 2D screen while piloting or moving tools in 3D, yet these technicians are originally trained in conditions where head movements do produce scene change. Distance estimation errors in any of these tasks have large potential costs in money and human life. The current findings suggest that NASA rover pilots, military drone pilots, scopic surgeons, and possibly other professionals, are likely to make vertical distance estimation errors due to the difference between their tasks and the environments in which they originally learned how to perform their tasks. A pilot might familiar with climbing more steeply over mountains when piloting a plane than a drone, for example, which could endanger the drone.

The current findings also suggest that studies with rudimentary virtual reality designs or unrealistic viewing conditions may be inappropriate for environmental distance estimation investigations, especially at large distances. A common technique used to study distance perception is to present impoverished stimuli in reduced laboratory environments. While impoverished visual scenarios can help isolate perceptual mechanisms through experimental control, such scenes were also exceedingly unlikely in the environments in which vision evolved in human ancestors. The current study suggests that, when used to study environmental distances, impoverished stimuli may not account for important distance cues. I suggest that environmental distance perception investigations pair impoverished stimuli with more realistic convergent measures or at least gauge participants' interpretation or understanding of the stimuli. Additionally, virtual reality methods should be as realistic as possible and gauge 'presence', or the believability of the method (Burdea & Coiffet, 2003; Sanchez-Vives & Slater, 2005). These techniques would permit the experimental control provided by impoverished or virtual stimuli while retaining acceptable ecological validity and generalizability.

Additional Findings

Order, sex, and body height.

Testing order, sex, and body height did not appear to affect distance estimates importantly. Evolved Navigation Theory would suggest that these factors should affect distance estimation insofar as they predict differential navigational costs over evolutionary time and no such differences are apparent.

Vertical-horizontal illusion.

The two-dimensional VHI estimates correlated with all estimates of virtual distances. This suggests that participants perceived these virtual surfaces more like 2D images than like 3D surfaces with falling costs. These points further suggests that the VHI is unlikely to be a 2D byproduct of mechanisms designed to navigate 3D surfaces with falling costs.

Experience questionnaire.

No clear relationship existed between any experience that I tested and any virtual distance estimates. Given the focus of the experience questions on falling, this lack of relationship with virtual estimates may further support the idea that participants did not perceive realistic falling costs associated with the distances that they estimated.

Acrophobia questionnaire.

If anxiety about falling alters any distance estimation, it should alter the longest vertical surface most, and it appears that this may have happened. Only the estimates of long vertical surfaces clearly correlated with any AQ items. Long vertical distance estimates correlated positively to a small degree with four AQ items. This would suggest that the virtual environment was not perceived entirely two-dimensionally. This encourages further investigation with more sophisticated virtual reality, as well as the use of the AQ in future environmental distance estimation research. I am currently collaborating with Hayhoe, Cormack, and Swan-Stone (personal communication) in order to conduct distance estimation experiments in sophisticated virtual reality.

General Discussion

These studies suggest that a previously unknown illusion in human visual perception drastically exaggerates environmentally vertical surfaces: the *environmental vertical illusion*. Data suggest that falling costs may directly produce this illusion. Greater severity of previous falling injury corresponded with decreased illusion magnitude, even though the illusion still existed at the more severe injury levels.

The environmental vertical illusion also appears specified to the realism of the falling costs, even across vertical surfaces. In a low-realism virtual reality method, participants estimated all distances accurately. This method appeared to pose an intermediate stage in between 2D and 3D processing, given that estimates universally correlated with the 2D VHI, yet the largest virtual vertical estimate also correlated with several acrophobia measures from 3D situations. The interface of 2D processing of 3D information is important in several applied areas, such as piloting and surgery, where errors produce large costs to money and human life.

Future research on the environmental vertical illusion would benefit from outlining the mechanisms and details of this previously unknown illusion. For instance, the environmental vertical illusion can only function effectively for large navigational distances and not distances within reach of the observer. Although distance overestimation may help us avoid falling by inhibiting us from choosing to climb the steeper of two surfaces, overestimation could actually promote a fall if, for example, we overestimated the grasping distance while climbing a tree. Overestimation as a means to avoid falling cost should only function with distances that we navigate and not distances with which we physically interact.

Multiple lines of evidence indeed suggest a functional division between action and visual perception pathways. Neuroanatomical evidence from brain pathology suggests largely segregated visual awareness and visually guided action pathways (Goodale, Milner, Jakobson, & Carey, 1991). Perception and memory research suggests separation between navigational perception and action (Oudejans, Michaels, & Bakker, 1996; Witt, Proffitt, & Epstein, 2004). Pélisson, Prablanc, Goodale, and Jeannerod (1986) found that participants could manually track a visual stimulus during saccades without view of their pointing hand, even when participants report no viewed stimulus movement. Servos, Carnahan, & Fedwick (2000) even found that participants' actions (grasping) were immune to a visual illusion on a figure, although it is unclear if participants were able to view their hands during grasping. The environmental vertical illusion is unlikely to occur in action pathways, but there are many more specifics of the illusion to investigate.

The current studies may suggest that distance estimates are subject to anchoring effects. Study 1 participants received distance indicators that began at the shortest possible distance and those participants underestimated (horizontal) distances by a slight amount. Study 2 participants, however, received distance indicators that began at random locations both larger and smaller than the actual distance and those participants estimated horizontal (and vertical) distances accurately. It will be important that future research use random starting locations for distance indicators in order to control for anchoring effects.

It would also be interesting to determine the extent of anchoring effects across distances empirically.

The current studies may suggest that textrue discontinuities may not importantly affect the observed distance estimates. I replicated the texture discontinuity from Study 1 in the virtual environment of Study and participants did not underestimate the horizontal surfaces in Study 2.

An important direction with this research will be to use high-fidelity virtual reality methods that provide orientation and location tracking, as well as binocular perspective and other immersive capabilities. Such a method could provide a highly realistic setting that may replicate the findings from Study 1. It would be interesting to use such methods whereby we gradually remove different visual components in order to see which stimuli produce the environmental vertical illusion.

Perceptual Navigation Cost Theories Revisited

Although distance estimation was one of the first topics investigated in psychology (Fick, 1851, cited in Finger & Spelt, 1947; Oppel, 1854, cited in Hicks & Rivers, 1906), no research previously identified the apparently ubiquitous, large magnitude environmental vertical illusion in everyday perception. I predicted this illusion from ENT by hypothesizing that asymmetrical navigational costs could co-opt distance estimation as a means of cost avoidance over evolutionary time. This would result in environmental vertical overestimation due to falling costs associated with navigating those surfaces.

Foreshortening of receding horizontals (as posed by Segall, Campbell, & Herskovits) would have predicted that participants in both of the current studies should have estimated accurately at both orientations because there was equal and minimal foreshortening across orientations. Evidence of the environmental vertical illusion fails to support this theory. Additionally, the descent illusion, discussed below, refutes the claims by Segall, Campbell, and Herskovits.

Gravity theory could support the existence of the environmental vertical illusion, but would suggest that the illusion exists due to the increased effort of navigating vertical surfaces, instead of increased falling costs. This difference in the hypothesized source of the environmental vertical illusion makes different testable predictions. Such experiments on the descent illusion directly refuted predictions made under gravity theory, as discussed below.

Affordance also failed to predict the current findings. If an organism fails to perceive an affordance, then perception of the object should not change due to that behavioral outcome. At no time were participants in the current studies led to believe that they would, or even could, climb the vertical surfaces, thus affordance cannot account for the resulting illusion relating to falling costs.

From evolved navigation theory, I would suggests that here is no need for an 'informed' decision, wherein the observer must perceive the specific costs posed by navigating a particular surface in order for distance overestimation to provide falling cost avoidance. Surfaces with falling costs are easily perceived and distance estimation is known to affect route choice. Natural selection needs only sufficient genetic variation in ancestral populations in order to fashion a ‘dumb’ system that need not even know that it sees vertical surfaces as longer—nor explicitly why it chooses to navigate raised surfaces less than others. Affordance is overly complicated, unnecessary, and fails to explain the current data.

Evolved navigation theory is the only available theory that accounts for the current findings, as well as related research discussed below.

Related Research

Distance estimation research is important due to the ubiquity of distance perception in animal species. Because navigation is prerequisite to nearly all animal behavior, navigational expense implicitly precedes the costs of most other behaviors, whether they be fighting, fleeing, feeding, or mating. This prerequisite makes navigational costs a powerful selective force in behavioral evolution across domains.

Previous research on the *descent illusion* (Jackson & Cormack, in press) found that participants overestimate vertical distances more from the top than bottom of a vertical surface. One might interpret such an effect as a byproduct of anxiety, fear, or arousal to standing on top of a height. However, the current studies suggest that the descent illusion does not result from anxiety or arousal per se. Participants in the current studies estimated a (horizontal) surface that would not likely pose falling costs and did not overestimate its length—even though they stood at the top of a height.

Anxiety, fear, or arousal would be poor indicators of the falling costs posed by a route because they arise for reasons other than falling costs. Anxiety, fear, and arousal are also likely metabolically costlier than length perception shifts. Further, anxiety, fear, and arousal presumably increase inaccuracy in non-beneficial circumstances, such as in the current studies when someone in a position with falling costs (i.e. standing at the top of a parking garage) needed to estimate a distance that did not pose falling costs (i.e. a horizontal surface below). If anxiety fueled this illusion, it would have made them *less* accurate and their estimates would reflect navigational costs less. Instead of anxiety or arousal, it appears that the navigation costs posed by a surface itself, along with one's expected ability to navigate that surface, likely drive these distance estimations in natural environments.

If, as suggested from ENT, likely interaction and falling costs (based on length and exocentric orientation) primarily drive the environmental vertical illusion, then it should occur at similar magnitudes across similar lengths and orientations—even with different participants in different settings. This is exactly what I have found.

Figure 9 displays estimates from Study 1 replotted from Figure 2 (solid lines), as well as distance estimates from a previous study (Jackson & Cormack, in press) as dashed lines. To compare the two lines with square data points in Figure 9 would be to compare distance estimates of exocentrically vertical surfaces while standing on the ground. We can see that overestimation magnitudes of vertical surfaces from the ground are almost identical—even though these estimates came from different participants, settings, visual angles, observer positions on the ground, head orientations, and estimation procedures. Participants perceive vertical, and thus navigationally costly, surfaces as longer than horizontal surfaces across disparate experiments.

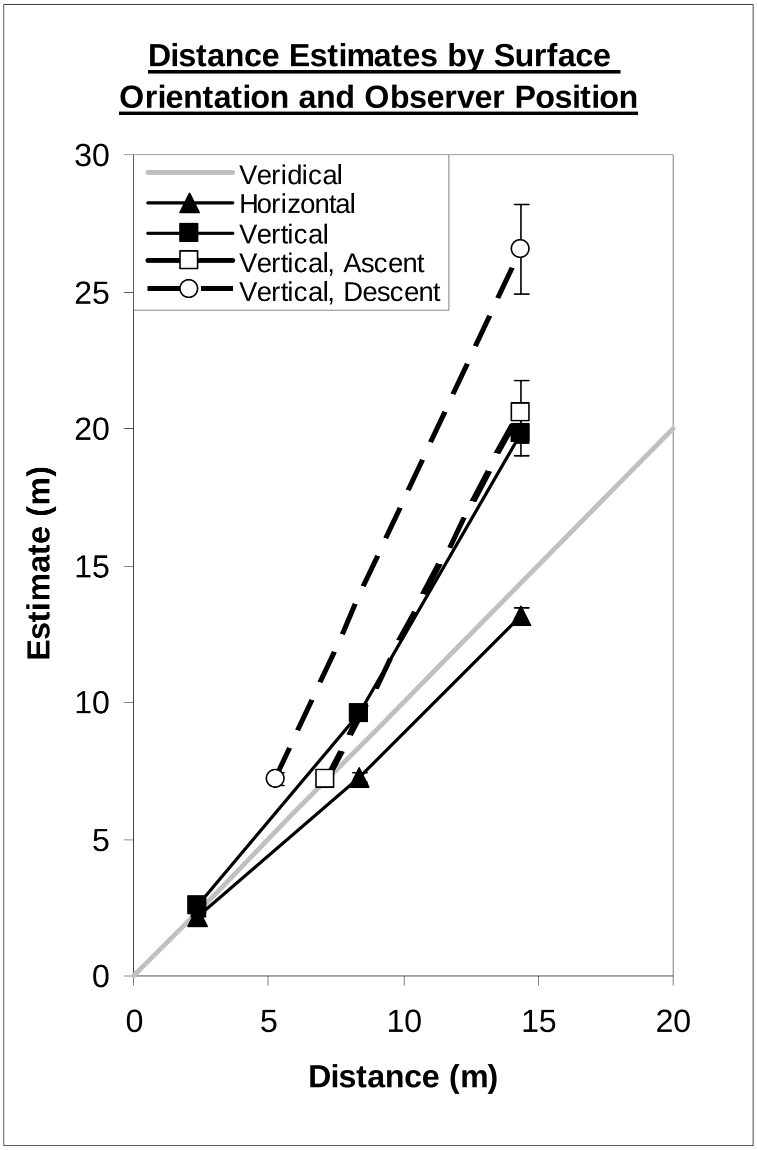


Figure 9. Mean distance estimates by stimulus length in meters replotted from Figure 2, compared to estimates from Jackson & Cormack (in press) depicted with dashed lines. Grey line indicates performing accurate estimation. Squares represent estimates while positioned on the ground, circles represent estimates of an exocentric vertical while standing on top of it. Error bars show 95% confidence intervals about the means.

Evolved Navigation Theory suggests that a way to increase the above overestimation would be to increase falling costs or risks. Falling risk happens to be greater when estimating a vertical distance while positioned on top of it, rather than on the ground, because people are more likely to fall when descending than ascending (Cohen & Lin, 1991; Haslam & Bentley, 1999; Svanstrom, 1974; Tinetti, Speechley, & Ginter, 1988). Thus, we should find even greater overestimation of a vertical surface when standing on top of it than when standing on the ground—if navigation costs drive this distance overestimation.

This is exactly what I found, as displayed with circles in Figure 9. This *descent illusion* results in heights perceived as taller while standing at the top than bottom by nearly a factor of two over the actual distance at 14 m. The differences in distance estimation in Figure 9 correspond to differences in falling cost probability, even across several studies.

The descent illusion was only predicted from ENT. The existence of the descent illusion directly contradicts predictions from foreshortening of receding horizontals (equal distance from top and bottom), gravity theory (greater from bottom than top), and affordance (equal distance from top and bottom). From no theory other than ENT could researchers have predicted the descent and environmental vertical illusions.

Additional Future Directions

For future studies, two important directions for ENT-directed research lie in 1) distance estimation and navigation across broad natural settings, and 2) individual differences in distance estimation.

Distance Estimation and Navigation Across Broad Natural Settings

The current studies isolated a specific environmental feature, 90 degree vertical surfaces, in order to determine the presence or absence of a previously unknown perceptual mechanism. This was an important step and I would now like to apply ENT predictions across broader varieties of environmental surfaces that humans encounter. There is a huge number of permutations of observer position in respect to environmental surfaces in 3D and ENT facilitates empirical predictions for distance estimation and navigation in many of them.

I am now researching which components compose the most important aspects of the environmental vertical illusion. In a current study, participants unknowingly estimate the distance of the top and bottom halves of a building while standing on the ground below. I am trying to determine which half of a vertical surface contributes most to vertical overestimation. Predictions derived from ENT suggest that participants' estimates of the top half of the vertical surface will account for more of the overall overestimates of the entire surface. The top half of a vertical surface has greater falling risks because it would produce longer falls and because participants standing below it would be more fatigued by the time they reach it.

I am also researching how the slope of the surface upon which an observer stands may affect vertical distance estimates. Participants in this study estimate a vertical distance from both its top and bottom while standing on a slope that is angled either towards or away from the vertical surface. I predict from ENT that the slope of the surface should make little difference in distance estimates while positioned at the bottom of the vertical surface because an increase or decrease in falling costs from one's current position on the ground poses little overall risk. However, I predict that standing on a slope angled towards a vertical surface while standing above the vertical surface should increase distance estimates because doing so directs the observer's center of gravity to fall towards the vertical surface. I predict that standing on a slope angled away from the vertical surface while standing at its top should either decrease distance estimates, because doing so makes the observer more likely to fall away from the vertical surface, or slightly increase distance estimates due to standing on a raised, less stable surface.

Individual Differences in Distance Estimation

It will also be important in future research to understand the large individual differences in distance estimation. The current data and all previous studies of distance estimation to my knowledge suggest that large individual differences pervade human and non-human distance estimation. However, data have previously supported no succinct explanation of the origin of these individual differences, possibly due to the dearth of causal theories of distance estimation. Evolved navigation theory puts forth an empirically testable predictive framework for investigating individual differences. It suggests that navigation costs posed selective pressure that shaped human perceptual and cognitive mechanisms over evolutionary time. This suggests, for example, which specific experiences across lifespan, or differences in navigational costs in different environments, might predict distance estimation differences across individuals or cultures.

A previous study of infant navigation highlights one set of suggestions under ENT. Gibson and Walk (1960) found that infants are willing to move onto a visual cliff with little distress until the stage of development where they begin to crawl. Around crawling age, infants begin to show great distress when their mothers try to coax them across a visual cliff. It is interesting under ENT that even infant navigation appears specified, not only to falling costs, but also to the appropriate developmental stage when such falling costs become possible.

In a current study, I am testing a population of acrophobics in order to determine the effects of experience in distance perception. As mentioned above, acrophobics tend to have less experience with heights than non-acrophobics. In the current studies, we see that lower levels of falling experience were associated with greater environmental vertical illusion, even though no amount of experience eliminated the illusion. These points indicate that height estimation mechanisms, in the absence of experience, default to the higher levels seen in the population. This suggests that acrophobics may not just have a pronounced fear to a normal stimulus, but may actually have a more normal fear response to an exaggerated stimulus. Acrophobia treatment might therefore benefit as much from training accurate distance estimation as it does from training fear and anxiety management. Distance estimation itself may be able to serve as an index of acrophobia and, thus, a continuous metric for measuring acrophobia treatment efficacy.

Understanding the multiple sources of individual differences in distance estimation holds other important applications. The greatest mortality risk during flights are commonly during take-off and landing, while height perception is one of the most important human-factors tasks at such points. Pilot screening, training, and retraining could benefit from knowing how to index distance estimation differences, as well as understanding how best to train appropriate distance estimation for specific aircraft and piloting scenarios.

Conclusions

These studies suggested that everyday visual perception is unknowingly subject to large-scale illusions on ubiquitous environmental surfaces. Participants overestimated environmentally vertical surfaces and did so to an increasing degree with longer surfaces, neither of which occurred with environmentally horizontal surfaces. I title this illusion the *environmental vertical illusion*. The severity of previous injury from a fall related to the degree of illusion such that more severe previous falling injuries were associated with lower illusion magnitudes, even though the illusion is still present at higher injury severities. I predicted these data from hypotheses derived from *evolved navigation theory* (ENT), which focuses on how navigational costs over evolutionary time can shape cognitive and perceptual mechanisms.

Virtual reality data suggested that unrealistic falling costs failed to produce the environmental vertical illusion, even with apparently vertical surfaces. Virtual reality methods also suggested that distance estimation from fixed visual displays deviated from natural distance estimation in important ways that hold implications for tasks involved in piloting and surgery. Data from physical and virtual reality suggested that no clear relationship existed between the 2D Vertical-Horizontal Illusion and 3D distance estimates gathered here.

The current findings hold implications outlined under ENT for areas such as anxiety disorders, piloting, surgery, individual differences, and visual stimuli design. However, these findings may be most important because distance and orientation perception occurs constantly in most visual systems and, consequently, most behaviors. Understanding how distance perception occurs thus helps us to understand one of the most common of all psychological experiences. These data suggest that a primary component of human visual experience is illusory. However, with a causal theory rooted in evolution (ENT), we may be able to predict and better understand these important features of human psychology.

Appendix A: Experience Questionnaire

1) Do you have normal (20:20) vision?

Yes (Skip to question 2)

No

1.1) If you don't have normal vision, are you now wearing eyeglasses or contacts that correct your vision to 20:20?

Yes

No

2) Do you fear heights?

Not at all

Slightly

Moderately

Very much

Intense, possibly irrational, fear

3) What is your height?

feet

inches

4) What is your age?

years

---

5) What is your biological sex?

Female

Male

---

6) What is your primary race/ethnic background?

Asian/Asian American

Black/African American

Hispanic/Latino

White/Caucasian

Other

---

7) What is your academic major?

---

8) What is your current academic standing?

Freshman

Sophomore

Junior

Senior

Graduate

Non-student

---

9) As a child, how often did you climb things, like monkey bars, trees, or jungle gyms?

Never

Rarely

Occasionally

Frequently

All the time

---

10) How often do you climb things now? This could be anything vertical, like ladders, trees, or rocks.

Never

Rarely

Occasionally

Frequently

All the time

---

11) Do you have any indoor rock-climbing wall experience?

No experience

Some experience

Climb occasionally

Climb regularly

Expert

12) Do you have any outdoor rock-climbing experience?

No experience

Some experience

Climb occasionally

Climb regularly

Expert

13) Have you ever been injured from a fall?

Yes

No (skip to question 14)

13.1) If yes, how many times?

13.2) If yes, how badly were you hurt on the worst occasion?

Barely (like a small scrape)

Somewhat (like a large scrape or cut)

Significantly (something requiring a doctor's attention)

Severely (required hospitalization or a trip to the emergency room)

At risk of death (required prolonged hospital stay and possibly physical rehabilitation)

14) Do you have any aircraft piloting experience?

No experience

Some experience

Pilot occasionally

Pilot regularly

Expert

15) Which hand do you write with?

Right

Left

Appendix B: Screenshots of participant view during Study 2.

Each of the following screenshots orients with the top of the image on the left. Rotate the image 90 degrees clockwise to orient correctly. Screenshots were taken as follows:

Beginning of tour.

Beginning of short exocentrically vertical distance estimate.

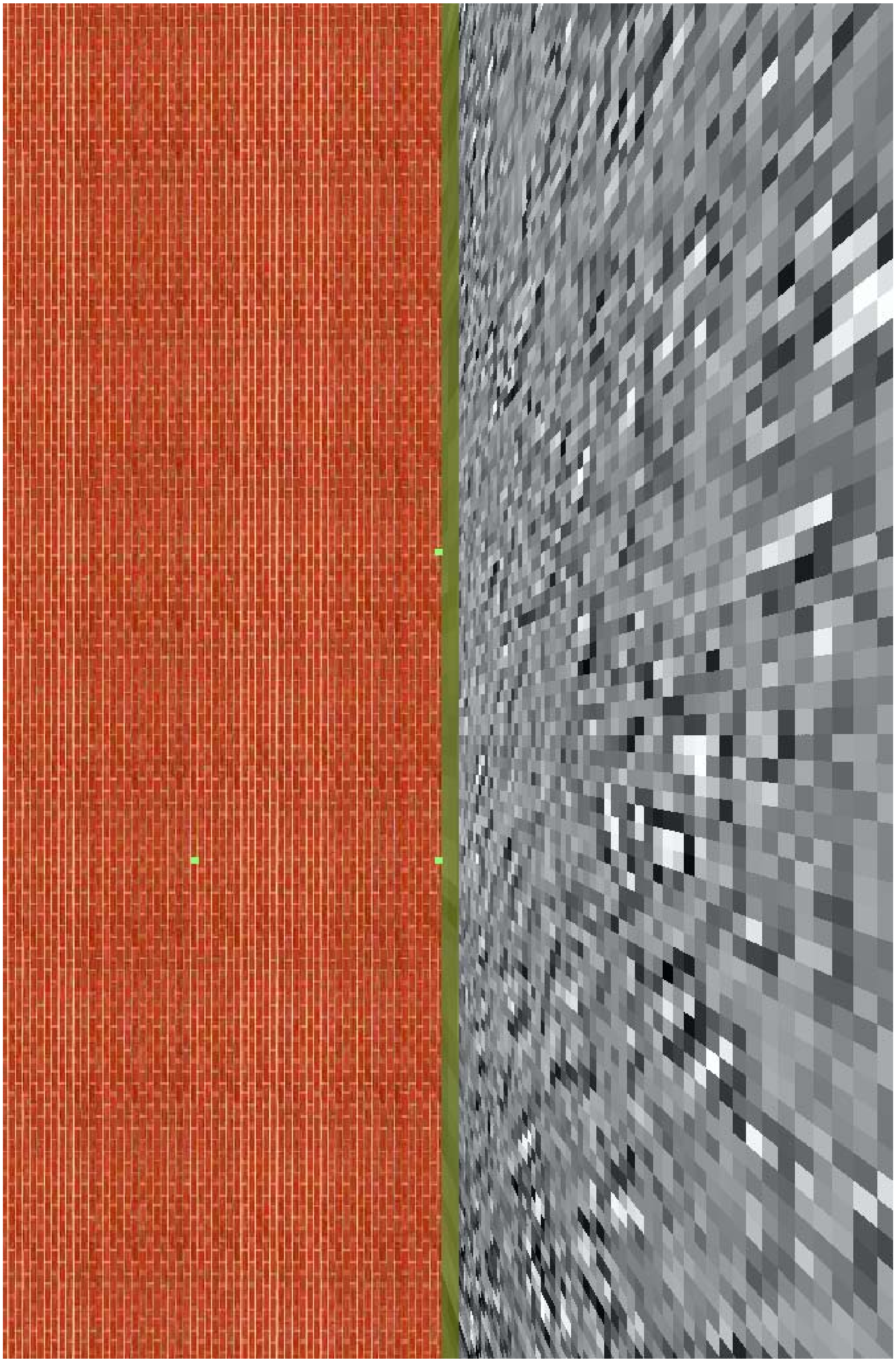
Beginning of medium exocentrically vertical distance estimate.

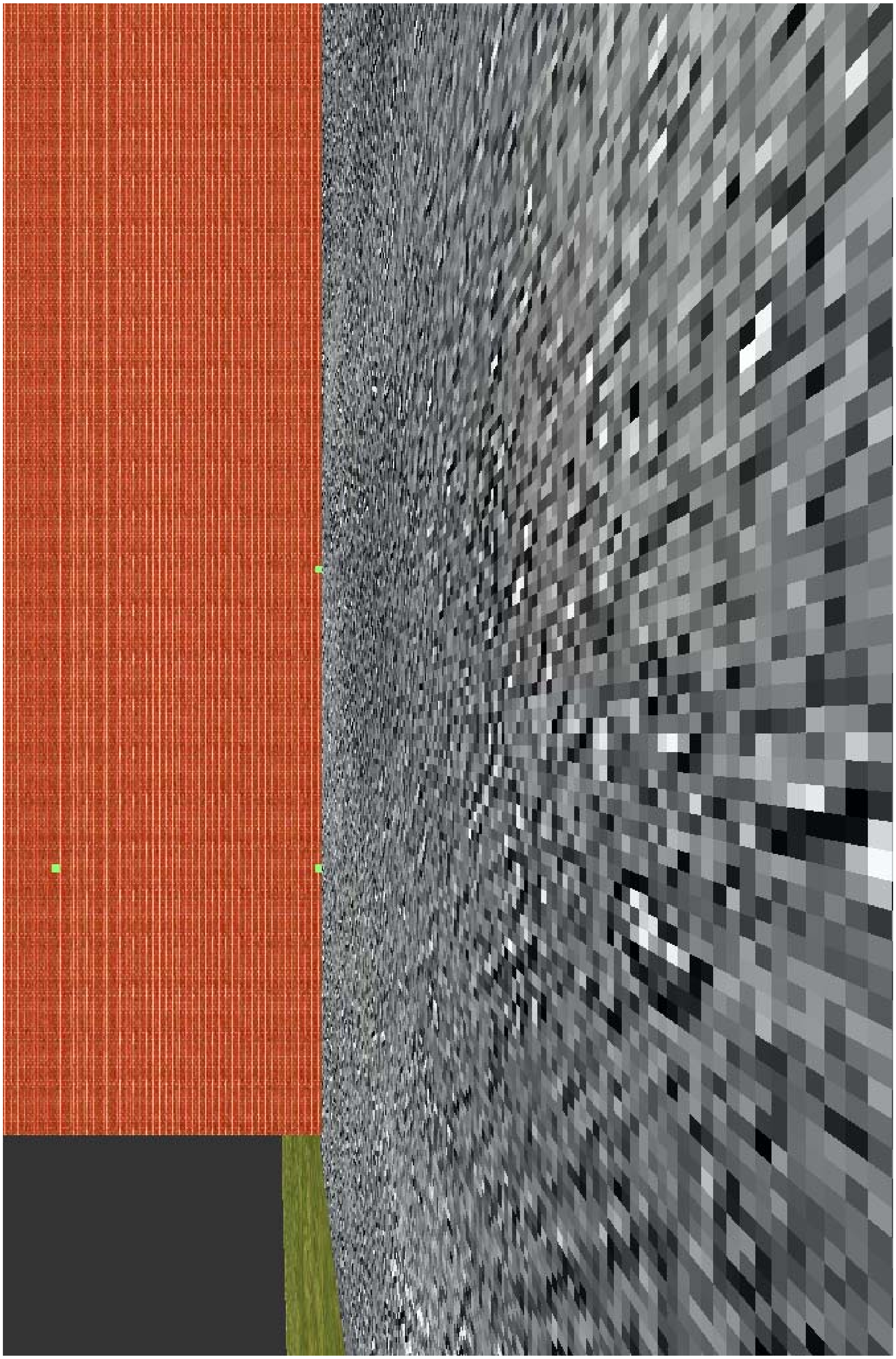
Beginning of long exocentrically vertical distance estimate.

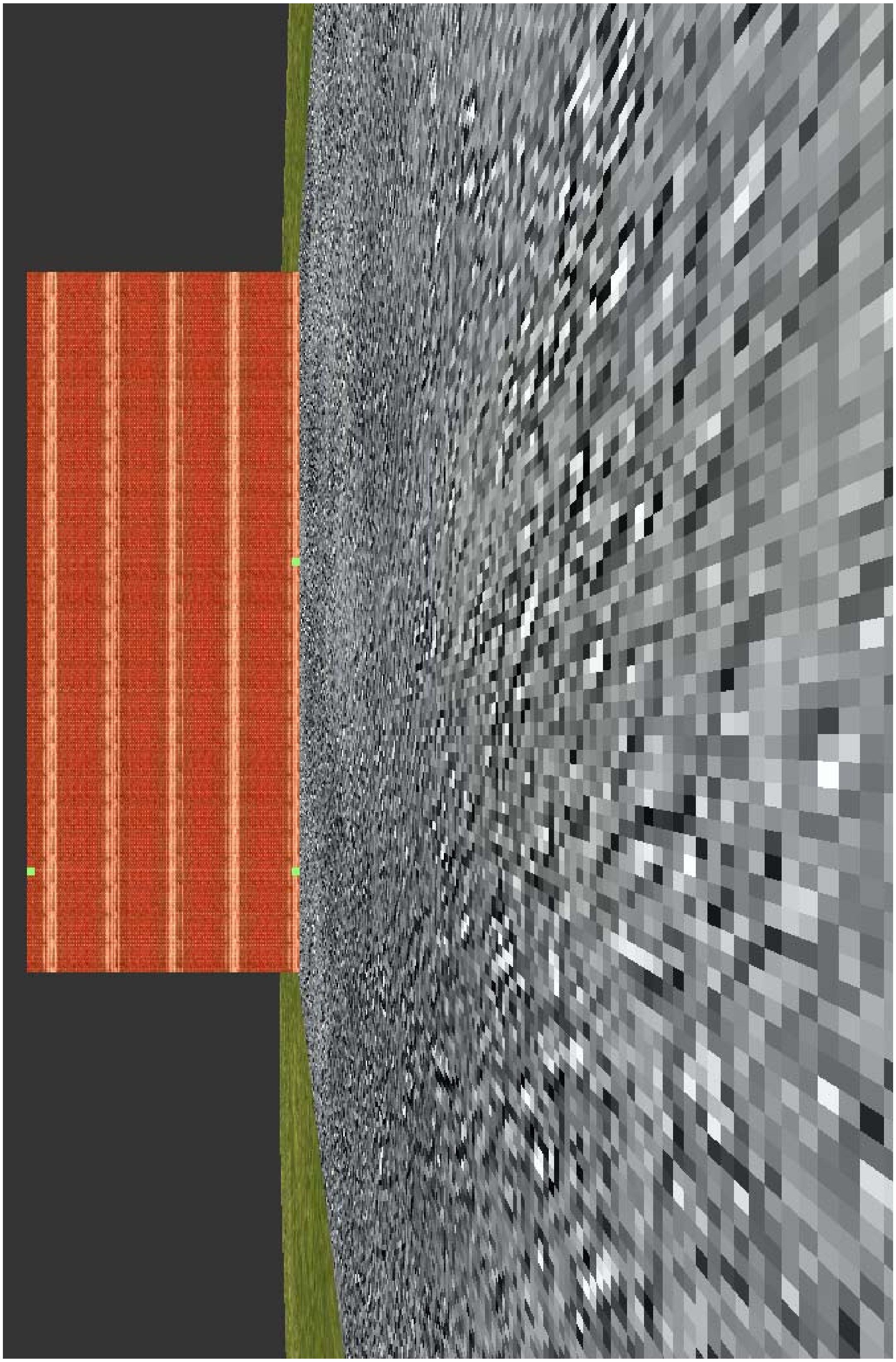
Beginning of short exocentrically horizontal distance estimate.

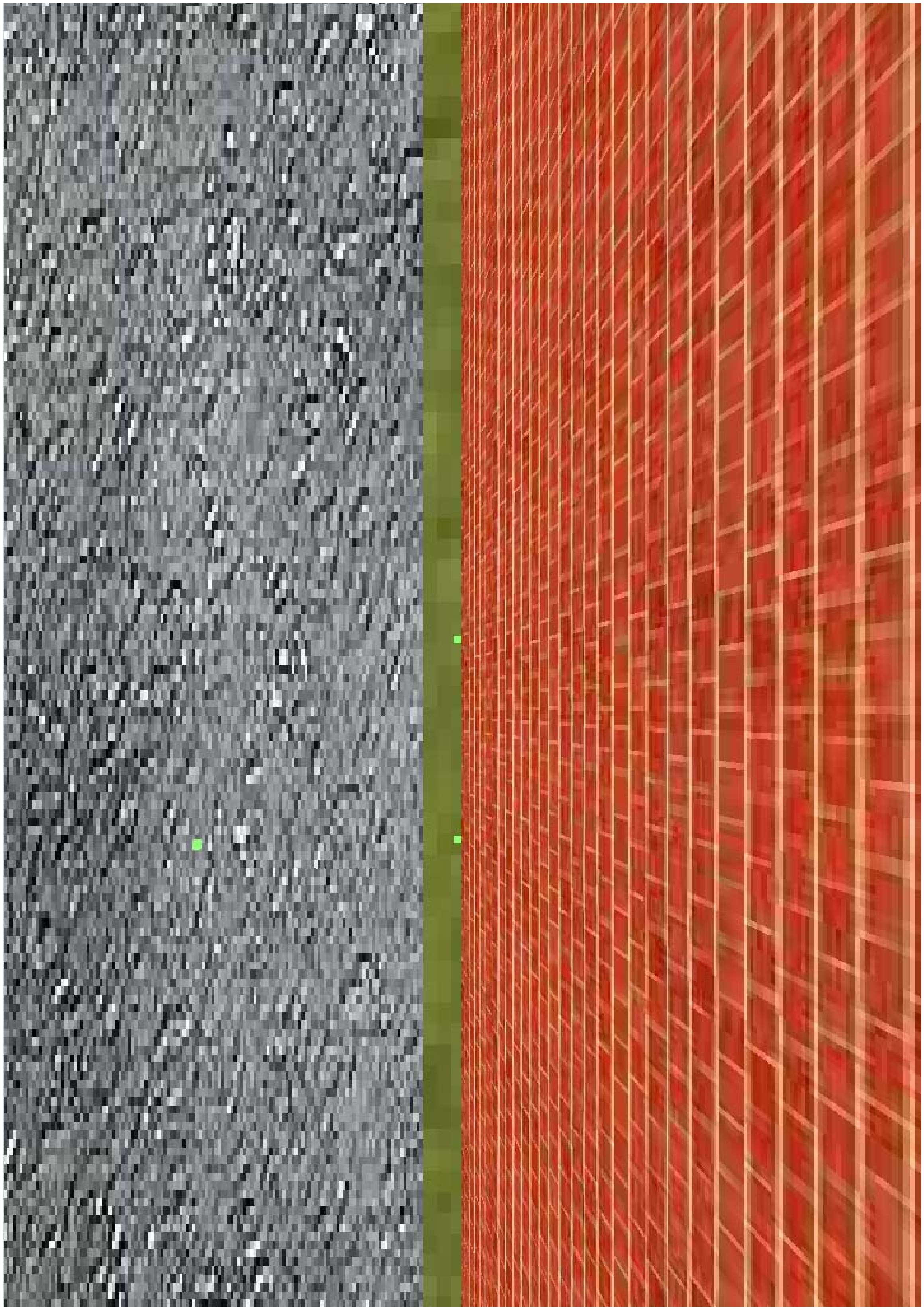
Beginning of medium exocentrically horizontal distance estimate.

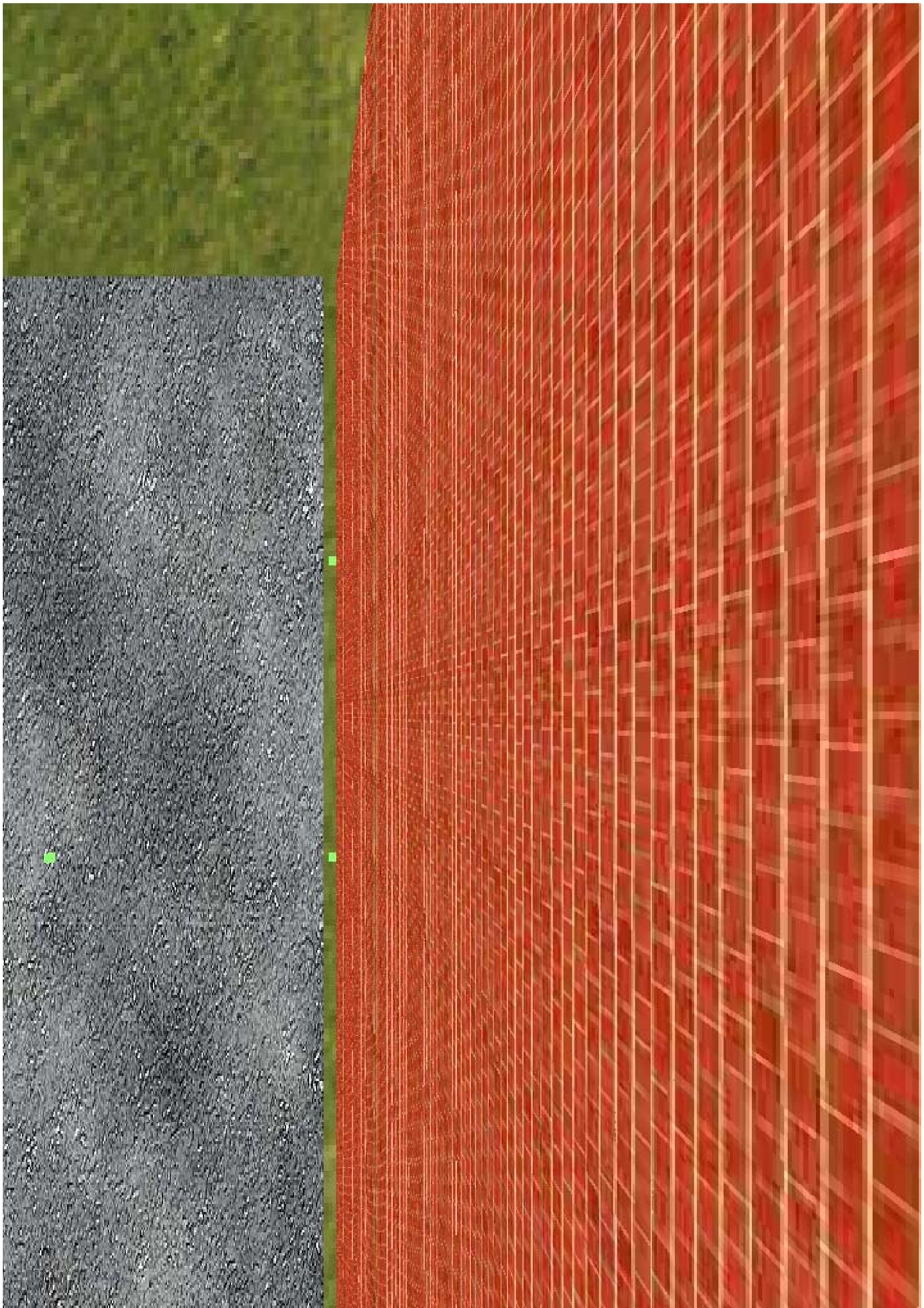
Beginning of long exocentrically horizontal distance estimate.

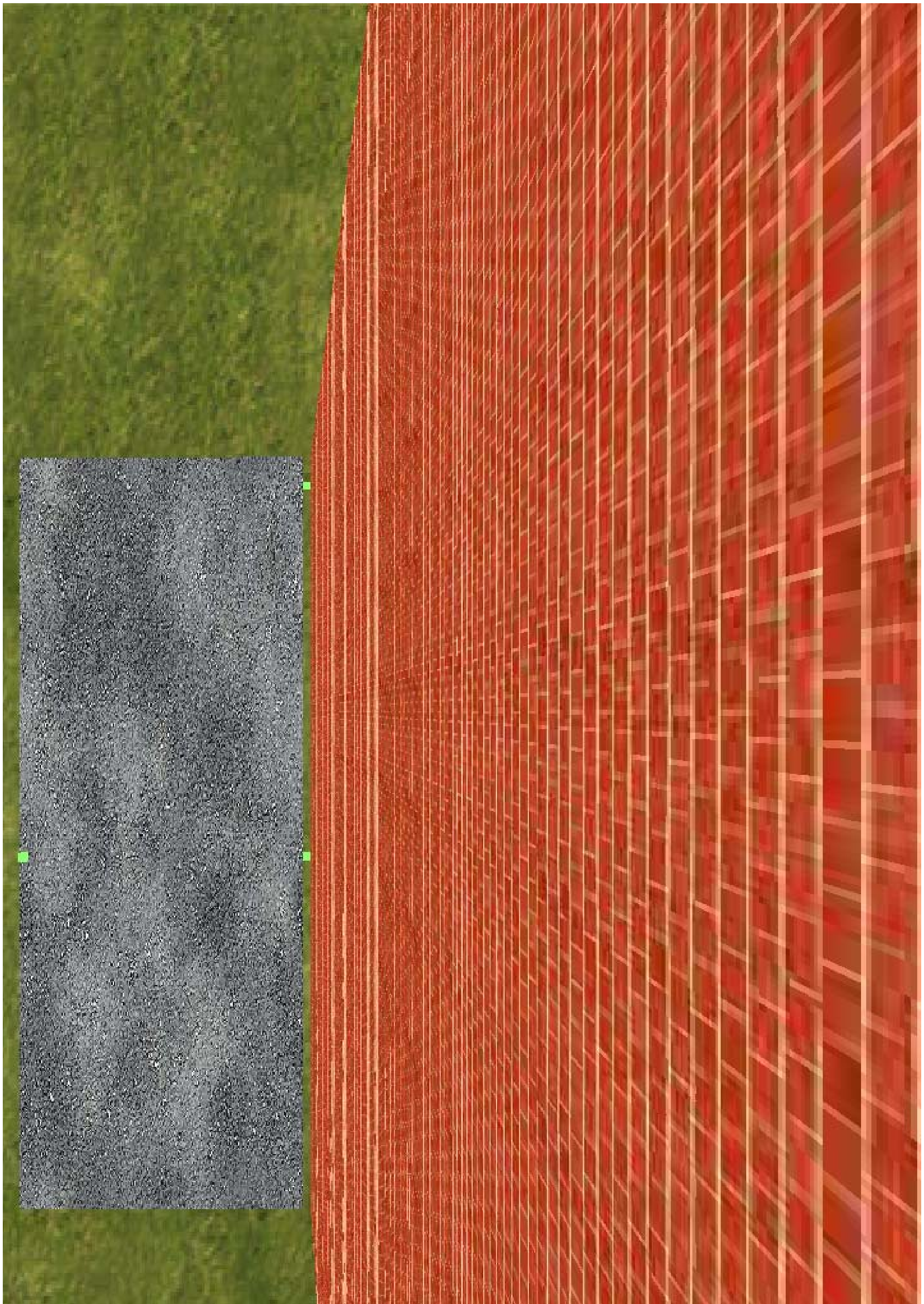












Appendix C: Acrophobia Questionnaire (AQ) from Cohen, 1977.

INSTRUCTIONS:

Below is a list containing situations involving height. Some people become anxious (tense or uncomfortable) and avoid these situations because of their fear. Please indicate how you would feel in each situation nowadays by checking one of the numbers below each item.

----
1. Diving off the low board at a swimming pool.

0 Not at all anxious,would not avoid situation
1
2 Slightly anxious,would not avoid situation
3
4 Moderately anxious,would try to avoid doing it
5
6 Extremely anxious,would not do it under any circumstances

----
2. Stepping over rocks crossing a stream.

0 Not at all anxious,would not avoid situation
1
2 Slightly anxious,would not avoid situation
3
4 Moderately anxious,would try to avoid doing it
5
6 Extremely anxious,would not do it under any circumstances

----
3. Looking down a circular stairway from several flights up.

0 Not at all anxious,would not avoid situation
1
2 Slightly anxious,would not avoid situation
3
4 Moderately anxious,would try to avoid doing it

5
6 Extremely anxious,would not do it under any circumstances

----
4. Standing on a ladder leaning against a house, second story.

0 Not at all anxious,would not avoid situation
1
2 Slightly anxious,would not avoid situation
3
4 Moderately anxious,would try to avoid doing it
5
6 Extremely anxious,would not do it under any circumstances

----
5. Sitting in the front of a second balcony of a theater.

0 Not at all anxious,would not avoid situation
1
2 Slightly anxious,would not avoid situation
3
4 Moderately anxious,would try to avoid doing it
5
6 Extremely anxious,would not do it under any circumstances

----
6. Riding a ferris wheel.

0 Not at all anxious,would not avoid situation
1
2 Slightly anxious,would not avoid situation
3
4 Moderately anxious,would try to avoid doing it
5
6 Extremely anxious,would not do it under any circumstances

----
7. Walking up a steep incline during a country hike.

0 Not at all anxious,would not avoid situation

1
2 Slightly anxious,would not avoid situation
3
4 Moderately anxious,would try to avoid doing it
5
6 Extremely anxious,would not do it under any circumstances

----

8. Airplane trip across the country.

0 Not at all anxious,would not avoid situation
1
2 Slightly anxious,would not avoid situation
3
4 Moderately anxious,would try to avoid doing it
5
6 Extremely anxious,would not do it under any circumstances

----

9. Standing next to an open window on the third floor.

0 Not at all anxious,would not avoid situation
1
2 Slightly anxious,would not avoid situation
3
4 Moderately anxious,would try to avoid doing it
5
6 Extremely anxious,would not do it under any circumstances

----

10. Walking on a foot bridge over a highway.

0 Not at all anxious,would not avoid situation
1
2 Slightly anxious,would not avoid situation
3
4 Moderately anxious,would try to avoid doing it
5
6 Extremely anxious,would not do it under any circumstances

----
11. Driving over a large bridge (e.g., Golden Gate, George Washington).

0 Not at all anxious,would not avoid situation
1
2 Slightly anxious,would not avoid situation
3
4 Moderately anxious,would try to avoid doing it
5
6 Extremely anxious,would not do it under any circumstances

----
12. Being away from a window in an office on the 15th floor of a building.

0 Not at all anxious,would not avoid situation
1
2 Slightly anxious,would not avoid situation
3
4 Moderately anxious,would try to avoid doing it
5
6 Extremely anxious,would not do it under any circumstances

----
13. Seeing window washers 10 flights up on a scaffold.

0 Not at all anxious,would not avoid situation
1
2 Slightly anxious,would not avoid situation
3
4 Moderately anxious,would try to avoid doing it
5
6 Extremely anxious,would not do it under any circumstances

----
14. Walking over a sidewalk grating.

0 Not at all anxious,would not avoid situation
1
2 Slightly anxious,would not avoid situation
3
4 Moderately anxious,would try to avoid doing it

5
6 Extremely anxious,would not do it under any circumstances

----

15. Standing on the edge of a subway platform.

0 Not at all anxious,would not avoid situation
1
2 Slightly anxious,would not avoid situation
3
4 Moderately anxious,would try to avoid doing it
5
6 Extremely anxious,would not do it under any circumstances

----

16. Climbing a fire escape to the third floor landing.

0 Not at all anxious,would not avoid situation
1
2 Slightly anxious,would not avoid situation
3
4 Moderately anxious,would try to avoid doing it
5
6 Extremely anxious,would not do it under any circumstances

----

17. On the roof of a 10 story apartment building.

0 Not at all anxious,would not avoid situation
1
2 Slightly anxious,would not avoid situation
3
4 Moderately anxious,would try to avoid doing it
5
6 Extremely anxious,would not do it under any circumstances

----

18. Riding on an elevator to the 50th floor.

0 Not at all anxious,would not avoid situation

1
2 Slightly anxious,would not avoid situation
3
4 Moderately anxious,would try to avoid doing it
5
6 Extremely anxious,would not do it under any circumstances

----

19. Standing on a chair to get something off a shelf.

0 Not at all anxious,would not avoid situation
1
2 Slightly anxious,would not avoid situation
3
4 Moderately anxious,would try to avoid doing it
5
6 Extremely anxious,would not do it under any circumstances

----

20. Walking up the gangplank of an ocean liner (A gangplank is used to board and leave a ship at a pier)

0 Not at all anxious,would not avoid situation
1
2 Slightly anxious,would not avoid situation
3
4 Moderately anxious,would try to avoid doing it
5
6 Extremely anxious,would not do it under any circumstances

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